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Terrain Disturbance Due to Summer Off-Road Vehicle Use in Central Keewatin, Northwest Territories, Canada

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Northern Affairs Program

Larry D. Dyke

Department of Geological Sciences, Queen's University, Kingston, (Ontario) K7L 3N6

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Perturbation de terrain pour l'utilisation en été de véhicules tout terrain dans le centre du Keewatin, Territoires du Nord-Ouest, Canada

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Abstract

The use of off-road vehicles can be an economic way of moving equipment in remote northern locations. In the Northwest Territories however, the risk that lasting erosion will be caused by summer use in permafrost areas requires that vehicles be used only when the surface is capable of sustaining travel without rutting. To accurately assess the impact of vehicle use in central District of Keewatin, two exploration companies participated in a monitoring program.

Till covers much of the uplands of central Keewatin and is in turn covered by peat along shallow valleys and in depressions. Peat is most susceptible to rutting, especially during early thaw. Churning and shearing produced by passage of a vehicle track generates a slurry which is easily flushed to the sides of the rut. Repeated trips re-expose the frost table to the air, accelerating the thaw. After two or three trips per day over one week, a rut deep enough to immobilize a vehicle can result. Runoff collected by the rut may cause further deepening, especially if erosion reaches frozen till.

A fibre content analysis of slurry and undisturbed peat indicates that little degradation takes place with a single trip under any terrain conditions. Living vegetation may be removed but the intertwining fibres of the peat remain intact. With a few more trips most of the slurry passes a 0.5 cm sieve, a state susceptible to erosion. It is concluded that one trip over any terrain at any time is insufficient to set off spontaneously advancing erosion. One company, in addition to observing this restriction on vehicle use, included vehicle handling in the planning of exploration during their second summer of work. This policy greatly reduced the occurrence of long lasting disturbance at their particular site.

Acknowledgements

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Nature of the Study

Light tracked vehicles (weight up to 4000 kg) can provide the most economic method of moving equipment during mineral exploration in remote areas. The summer use of vehicles on thawing permafrost soils may begin an unstable period of erosion however, as runoff, channelled by vehicle ruts, thaws and erodes permafrost. Land use permits allowing summer vehicle use in the Northwest Territories recognize this possibility and require that the surface be in a condition to fully support vehicles without rutting. It is therefore desirable that vehicle use does not produce disturbance that exceeds the ability of the terrain to revegetate or resist erosion. This study describes the response of till and peat in central District of Keewatin to summer off-road vehicle use. It provides an explanation of processes controlling the response of these materials to distrubance and suggests procedures for minimizing disturbance to vegetation.

Most studies of vehicle impact have depended on trials where vehicles pass over the same route many times in quick succession or on observations at some time up to years after the traffic occurred. Because the response of a given terrain may vary during the period of thaw and the manner in which a vehicle is used may also control the impact, observation over an entire summer of a vehicle-assisted operation may allow a measurement of impact under more realistic conditions. Accordingly, two companies requesting tracked vehicle use for the movement of diamond drills during the summer of 1980 were issued with land use permits on the condition that they participate in a monitoring program. They were also required to confine vehicle use to a geographically defined area and act to minimize disturbance.

In 1981 only one company requested vehicles. During this second summer, the company closely supervised vehicle use and restricted it to drill moves. This policy was adopted in the light of the previous summer's experience and it conformed with a new land use permit re-emphasizing the company's responsibility to reduce the level of impact. The establishment of vehicle use supervision by the company as an integral part of the exploration program resulted in a marked decrease in the level of disturbance during the second summer. While properties of surficial materials, climatic conditions and the nature of the field activity determined the potential for terrain disturbance, the operating strategy produced the actual outcome.

Approach to the Study

The immediate objective of the study was to measure the physical alteration of the terrain caused by a delineation drilling program using tracked vehicles to move drill rigs. This was achieved by quantifying disturbance due to the main components of the day to day operation:

1. development of ruts along repeatedly used supply routes.
2. effect of single passes on all types of terrain throughout the season.
3. disturbance caused by activity about drilling sites.

In order to explain the sensitivity of the terrain, several material properties or conditions were measured throughout the summer. The intent of this second phase was to determine what, if any, factors might control sensitivity and therefore allow predictions of sensitivity.

Location and General Character of the Sites

The two study sites are situated within the continuous permafrost zone in the southern part of the Keewatin District (Figure 1). The Lone Gull Lake site (64°27′, 97°42′W) is located approximately 80 km west of the settlement of Baker Lake and the Nogash Lake site (62°35′N, 98°37′W) is located approximately 240 km southwest of Baker Lake. From the standpoint of vegetation the sites are in the low arctic tundra zone (Zoltai and Johnson, 1978), being north of the treeline, although the Nogash site does boast scattered stands of spruce with occasional tamarack. Both sites are on rolling uplands with hill summits reaching elevations a little over 200 m but with local relief seldomly exceeding 50 m. Till of a well graded textural composition is by far the most common surficial material. In valley bottoms with a drainage gradient of less than 2% the till is overlain by a sedge peat up to one meter thick. At the Nogash site polygonalized peat mounds with relief of up to one meter increase this thickness locally. A peaty soil generally less than 20 cm thick is usually present on gentle slopes while hilltops are characterized by bare till exposed in the centers of frost-boils.

For the purpose of characterizing surficial material in terms of sensitivity to vehicle traffic, three material types were identified (Figure 2). Peat designates any purely organic soil in valley bottoms or poorly drained areas. It usually supports a cover of sedges and mosses. Till was classified according to its apparent tendency to dry once thawing began. The term well-drained till was assigned to areas where frost-boils were abundant and microrelief subdued (i.e., < 25 cm). Poorly-drained till was applied to areas having almost continuous vegetation cover, typically dwarf shrubs and heaths, and greater microrelief (25-75 cm).

Climate

The nearest continuous climate records for the area come from Ennadai and Baker Lake. The study sites lie between these two stations so the records can only be used as a general guide. The onset of high terrain sensitivity is most readily indicated by the disappearance of the annual snow cover. Observations on snow patch retreat at the Nogash site showed that ground beneath snow remains solidly frozen until completely bare. Thus the soils of any terrain will be essentially immune to disturbance at least until the date of snow disappearance. Pertinent data for a snow cover of one inch or less is given in Table 1 for Ennadai and Baker Lake (Potter, 1965).

Rainfall is the second important variable because it exerts the strongest influence on soil mechanical properties once the soil is thawed. From climatic data collected between 1941 and 1970, average yearly precipitation in the form of rain is about 165 mm at Ennadai and 125 mm at

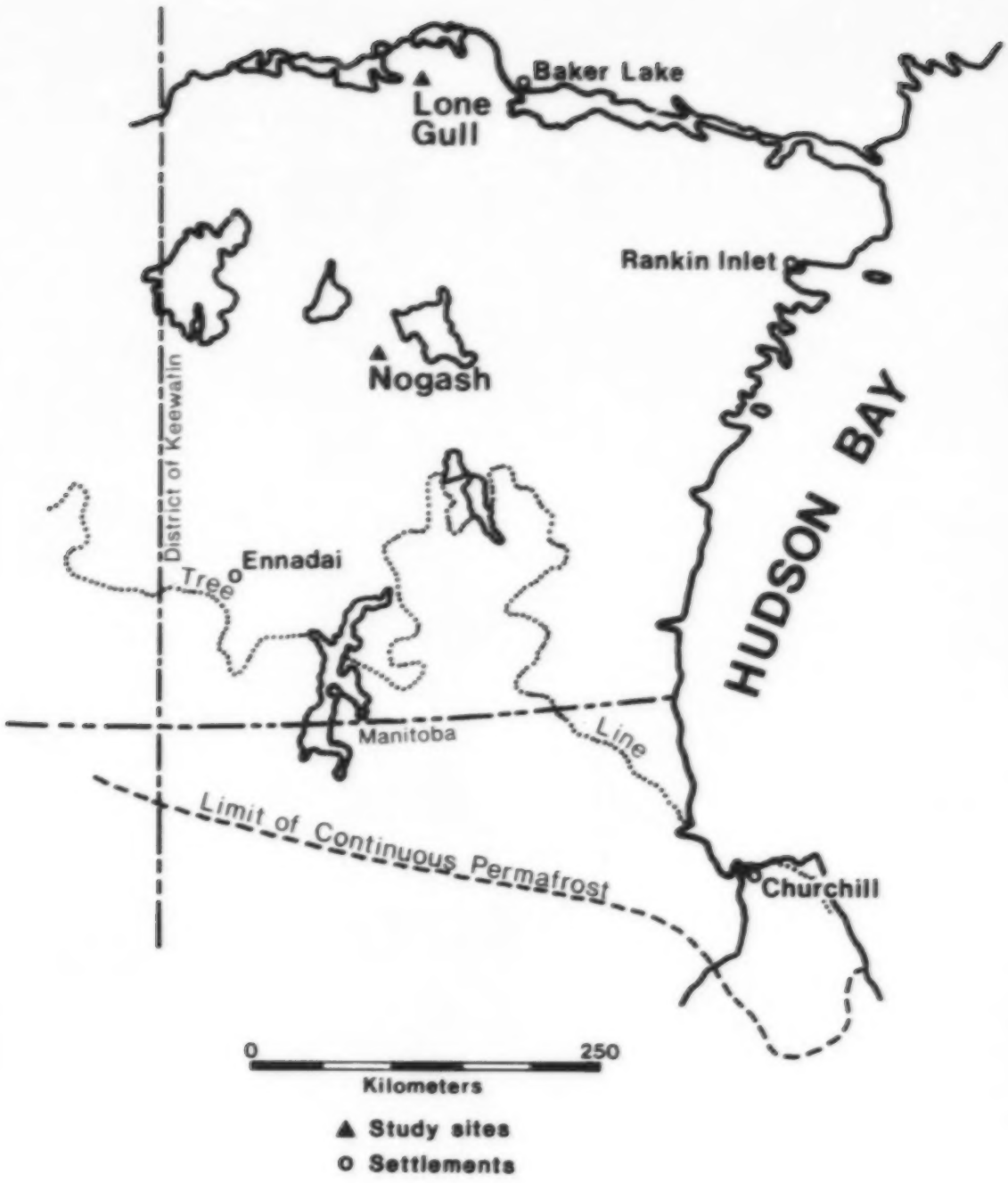

Figure 1 Map of western border of Hudson Bay showing location of study sites.

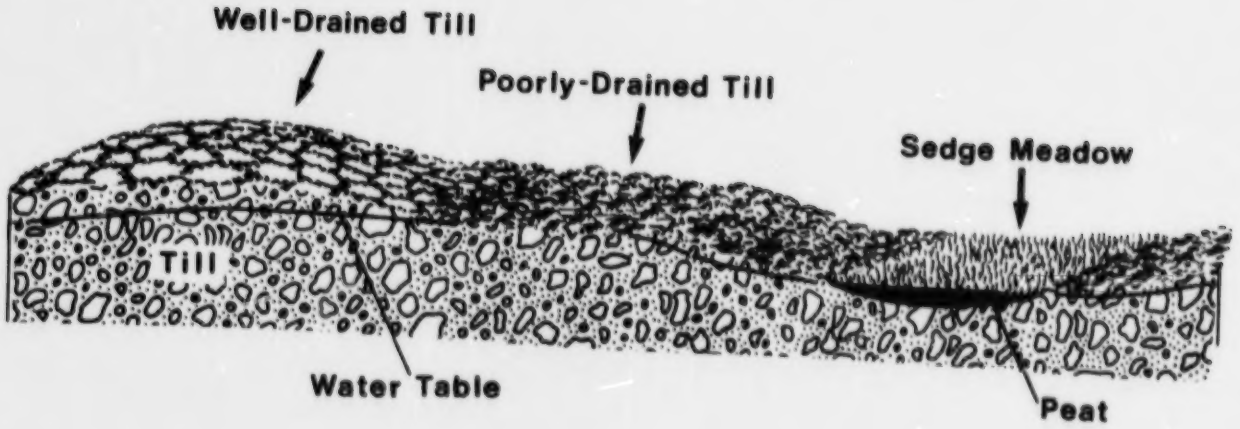

Figure 2 Drawing emphasizing surface appearance of till and peat.

Table 1 Occurrence of Snow Cover of 1 Inch (2.5 cm) or More

	Baker Lake	Ennadai
Date of first snow cover		
Earliest	Sept. 13	Sept. 15
Latest	Oct. 28	Nov. 2
Mean	Oct. 6	Sept. 27
Date of last snow cover		
Earliest	June 6	May 25
Latest	July 9	June 22
Mean	June 20	June 7

Based on data collected 1941-1965 (Potter,1965)

Baker Lake. The return interval of storms producing more than 30 mm of rain in 24 hours is slightly under 2 years at both stations. Figure 3 shows the rainfall records for the summers of 1980 and 1981 at the Nogash site. The fall near the end of August 1980 is extreme, amounting to 65 mm in 36 hours. However, about as much rain fell in a slightly longer time in mid-July, 1981 so it must be presumed that rainfalls of this intensity will occur during most years. On the other hand, comparison of the two records suggest that rain distribution throughout the summer is highly variable from year to year. Therefore it would be difficult to choose time intervals likely to have relatively wet or dry conditions.

Temperature has little influence on year to year soil conditions beyond assuring snow melt and ground thaw. For both sites thawing reached 50-60 cm (roughly half the active layer depth in till) at the end of the first month with average daily temperatures above freezing. Because average daily temperatures normally remain above freezing for approximately three months, enough thaw to create a potential for disturbance by off-road vehicle use will always occur.

Equipment

At the Nogash site two Bombardier Muskeg Tractors were used, each having an empty weight of 3200 kg (Figure 4). At the Lone Gull site one Bombardier Muskeg Carrier of approximately 3600 kg was used (Figure 5). Both models utilize an endless track consisting of fabric-reinforced rubber belts joined by steel crosslinks. Each track is 70 cm wide and is supported on two parallel rows of wheels. The tracks are therefore relatively stiff compared with single wheel designs since they project only 15 cm beyond either side of the two rows of wheels. This probably results in a more even distribution of bearing pressure on a highly compressible soil, resulting in increased traction. Average bearing pressure at the track surface is 11 kPa (1.6 p.s.i.) for either unloaded vehicle.

Several designs of drill trailer were used, the objective being a trailer that would be easily movable under most terrain conditions and yet provide a solid drilling platform. In 1980 a platform mounted on DC-3 aircraft tires was tried at the Nogash site (Figure 6). While performing adequately on frozen ground, the device was easily mired in thawed till areas due to the small bearing area of the tires. Two vehicles were often required for a move and on at least one occasion an entire 12 hour shift was expended in freeing one of the tire-mounted trailers. In 1981 platforms mounted on four independent tracks (same track design as the towing vehicle with front tracks steerable) were tried (Figure 7). This resulted in bearing pressures for the 5400 kg weight of trailer plus drill (17 kPa, 2.5 p.s.i.) approaching that of a vehicle and produced relatively trouble-free towing.

At Lone Gull sleds resting on two steel runners 25 cm wide were used (Figure 8). Bearing pressure including the drill was equal to the track-mounted carrier. The average force required to pull the sled on level ground amounted to approximately 35% of the carrier weight while the tracked carrier required approximately 25% of the carrier weight as a drawing force. In both cases the drawing force increased to 50% of the

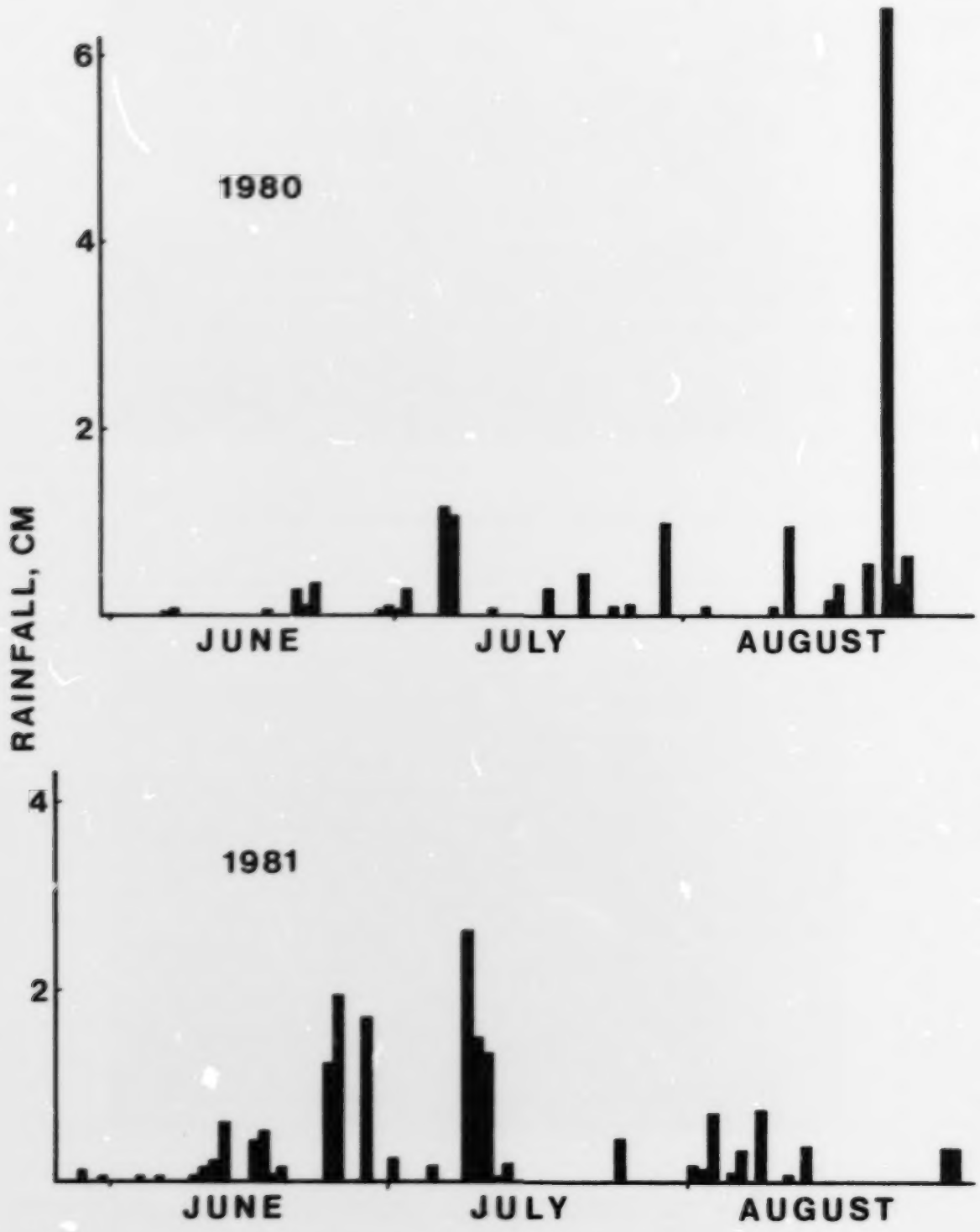

Figure 3 Daily rainfall for summers of 1980 and 1981 at Nogash site.

Figure 4 Bombardier Muskeg Tractor.

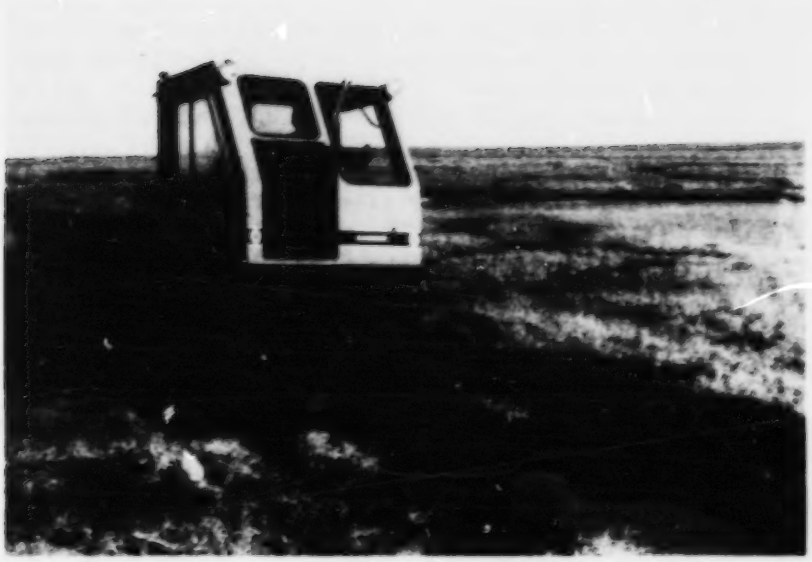

Figure 5 Bombardier Muskeg Carrier. Note movement of peat slurry ahead of tracks.

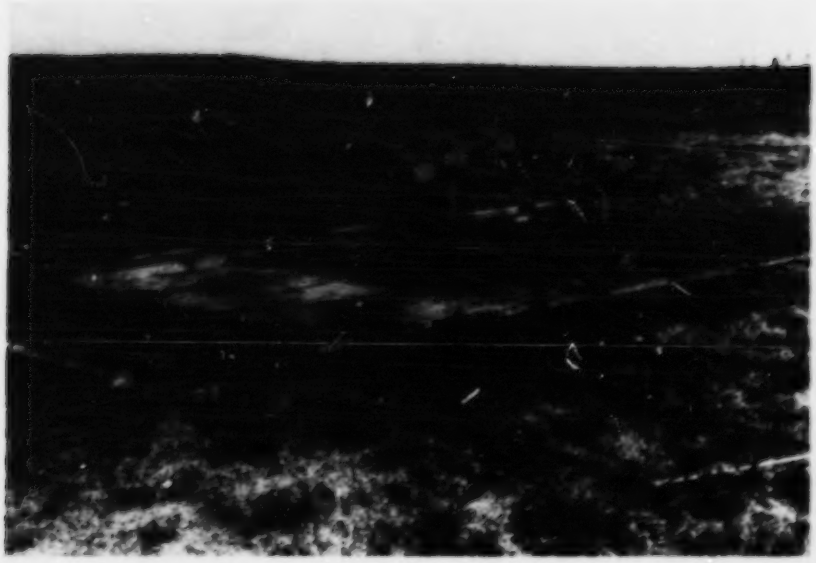

Figure 6 Wheel-mounted drill trailer used during 1980 at Nogash site.

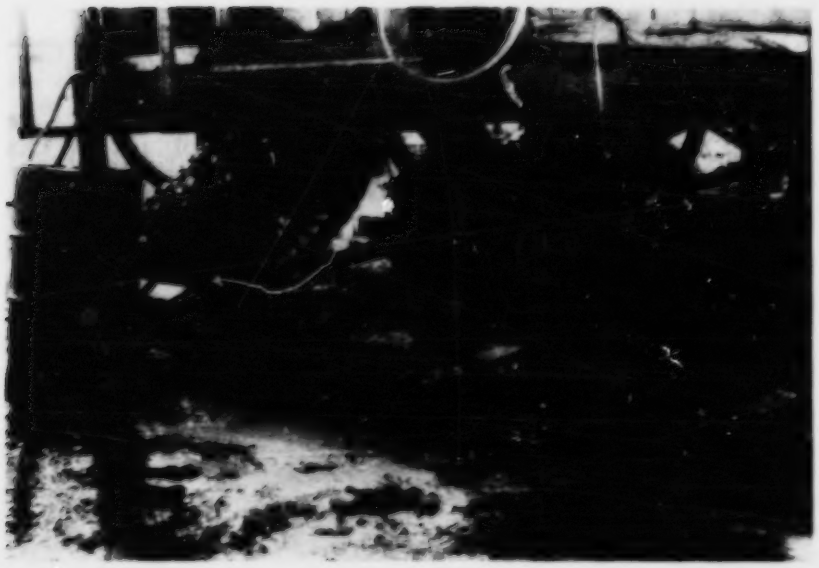

Figure 7 Close-up of track-mounted drill trailer used during 1981 at Nogash site.

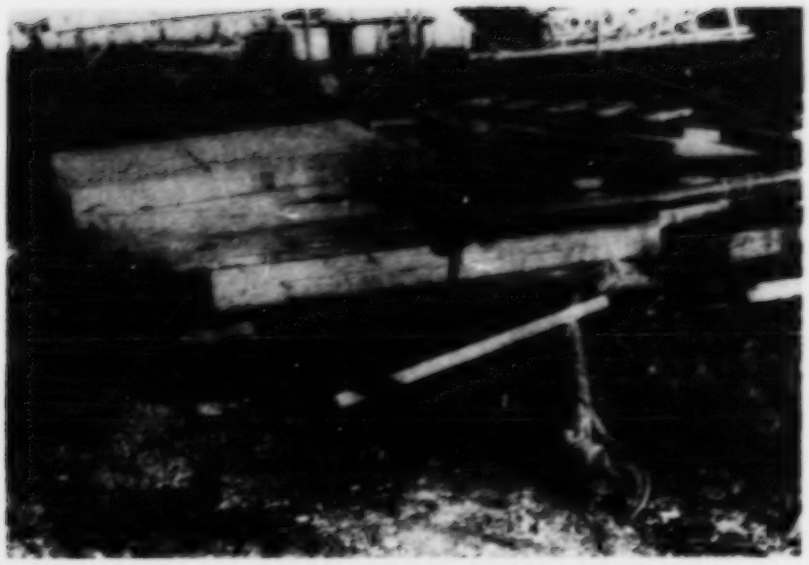

Figure 8 Sled-mounted drill trailer used at Lone Gull site during 1980.

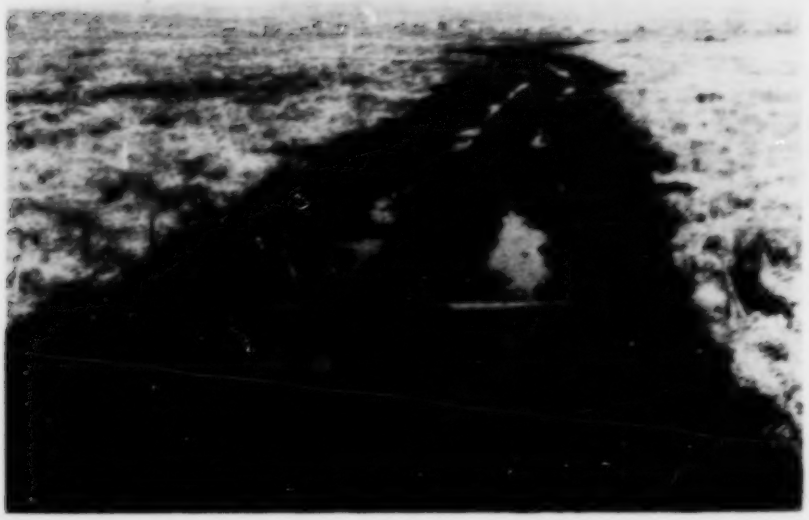

Figure 10 Original access route on peat at Nogash site after approximately 10 days of use (1-3 return tips per day). Photo taken June 20, 1980.

drawn weight where hummocks or boulders were traversed.

Detailed Descriptions of Sites, Vehicle Operation and Disturbance

Nogash Site

The Nogash site is located on an upland area mantled with up to 25 m of till. Bedrock exposures usually occur on hilltops and comprise only about one percent of the total area in which vehicles were used. In 1980, vehicles were confined to an area 0.5 by 2 km centered on a broad valley containing no well defined drainage course. Surface drainage, when it did occur, took place as a sheet flow. The valley bottom consists of hummocky fen supporting dwarf birch and willow up to one m high. Otherwise a continuous cover of mosses and sedges is present. The hummocks usually consist of peat and range in height between 0.25 and 0.75 m. The fens also contain many flat, sedge-covered areas, which hold the largest areas of standing water early in the thaw and after heavy rains. Upslope, hummocky terrain persists but gradually decreases in relief to a minimum on hilltops. Frost boils are most numerous and well developed on hilltops and on thin (i.e., < 1 m thick) till.

In 1980 a route following the valley bottom was repeatedly used by vehicle traffic between base camp and the general area of drilling (A in Figure 9a, also Figure 10). Traffic on this route began after snow had disappeared but before thaw had progressed deeper than 10 cm in peat. Drill rig towing only accounted for one trip between any two drilling sites, otherwise all traffic over this route was for supply of the rigs.

Between late May and June 10 the valley trail progressed to a distance of one km from the base camp as successively distant drill sites were occupied. Figure 11 shows a longitudinal profile of rut depth along 800 m of this route, measured on June 13. The peat shown on the profile underlies hummocky sedge fens. Otherwise till is exposed where the route crosses valley sides having only a thin organic soil. The final 150 m of this profile was developed between June 10 and 13 and shows the rut depth to approach 40 cm despite a thaw depth of no greater than 15 cm in peat at the time. Traffic continued at the rate of one or two return trips per day until mid-July. After mid-July the valley bottom route was abandoned and a new access route established on well drained till about 100 m south. This new route (B on Figure 9a) converged with the old, meeting it at the point represented by the 800 m mark on the profiles in Figure 11.

The August 23 profile of the abandoned valley route on Figure 11 was recorded one day after the heaviest rain of the year, the previously mentioned 65 mm fall in 36 hours. Because that portion of the route between 500 and 800 m in Figure 11 coincided with the valley bottom, the ruts collected the runoff (with flow from right to left on the profile) and became the primary local drainage. Along this portion most of the remaining peat was removed, exposing till. The increased irregularity of the profile results from the formation of plunge pools downstream of boulder concentrations in the till (Figure 12). At the 400 m mark the flow left the trail. The June 4, 1981 profile shows the effect of continued

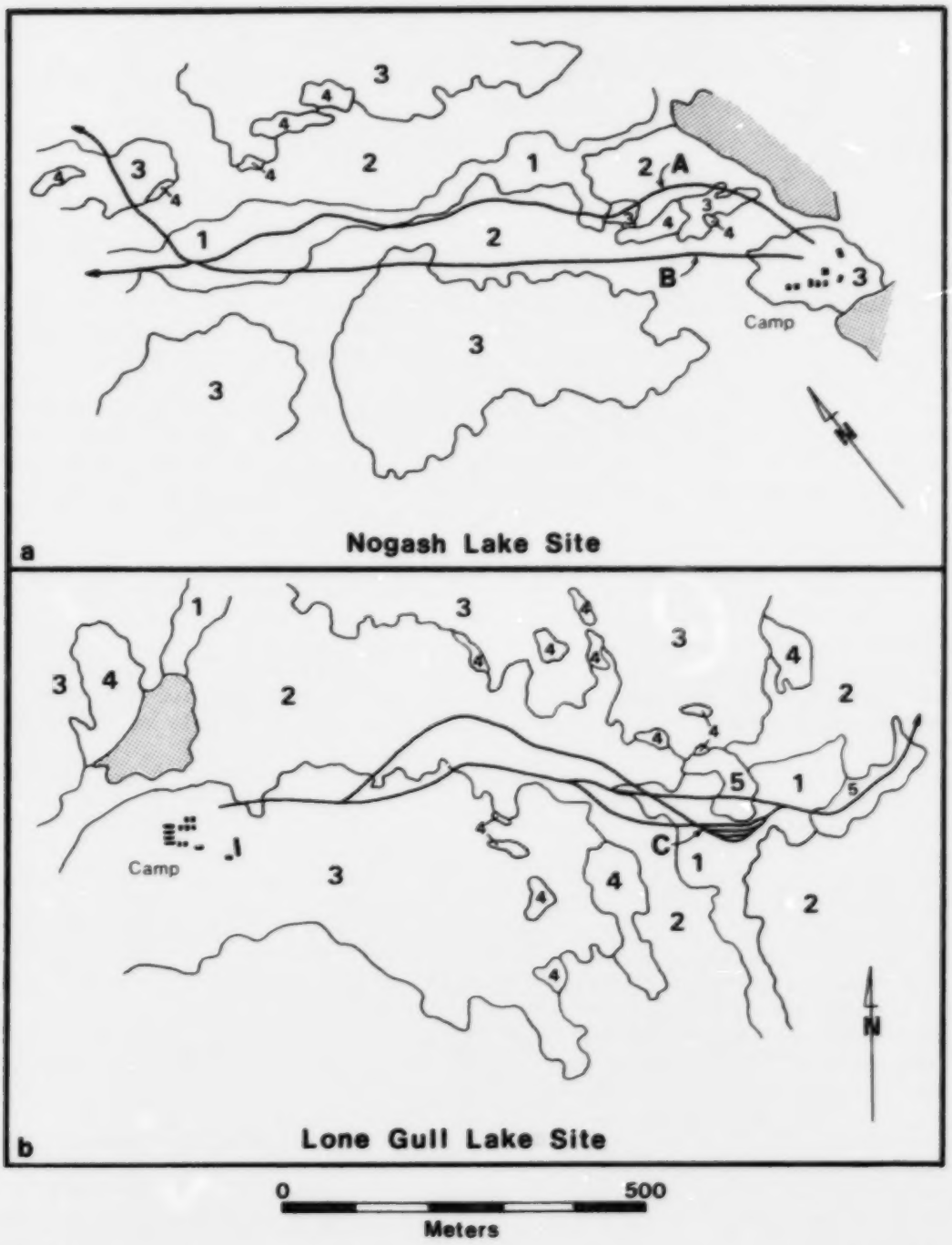

Figure 9 Maps showing tracked vehicle access routes (heavy lines) between camps and main drilling areas (A - original main access route abandoned in mid-July, 1980; B - new access route established in mid-July, 1980; C - area of multiple route abandonments in fen), also surficial materials as follows: 1- peat, 2- poorly-drained till, 3- well-drained till, 4- bedrock or bedrock with less than 1 m of till, 5- outwash.

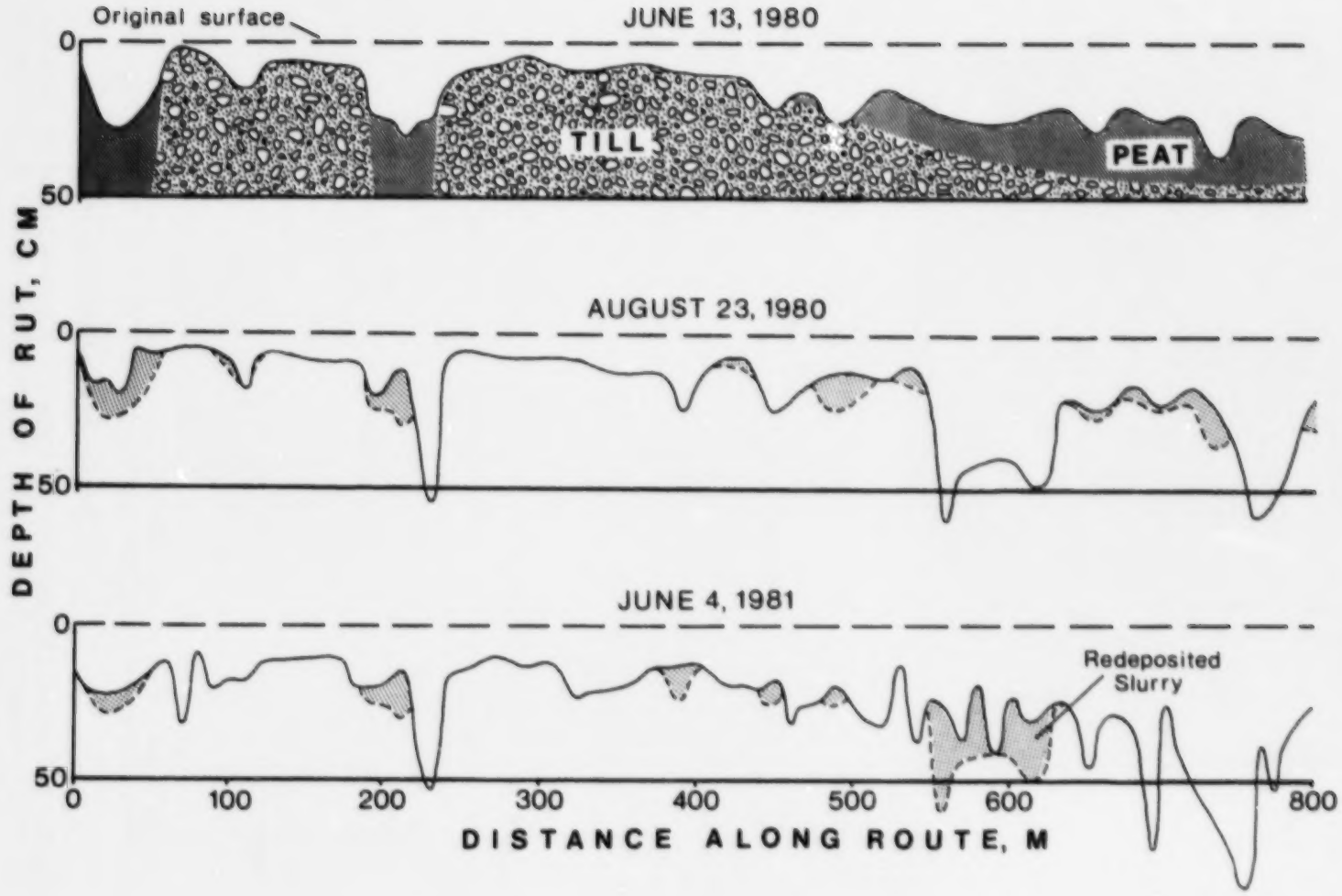

Figure 11 Longitudinal profiles of original access route at the Nogash site (route A in Figure 9a).

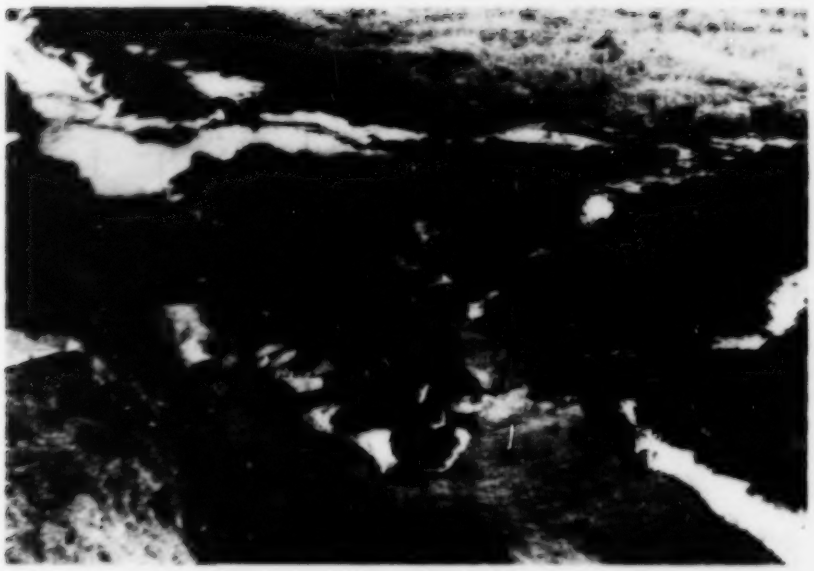

Figure 12 Original access route at approximately the 700 m position on profiles in Figure 11. Photo taken June 1, 1981. Note removal of till matrix to reveal till boulders, also plunge pool immediately downstream.

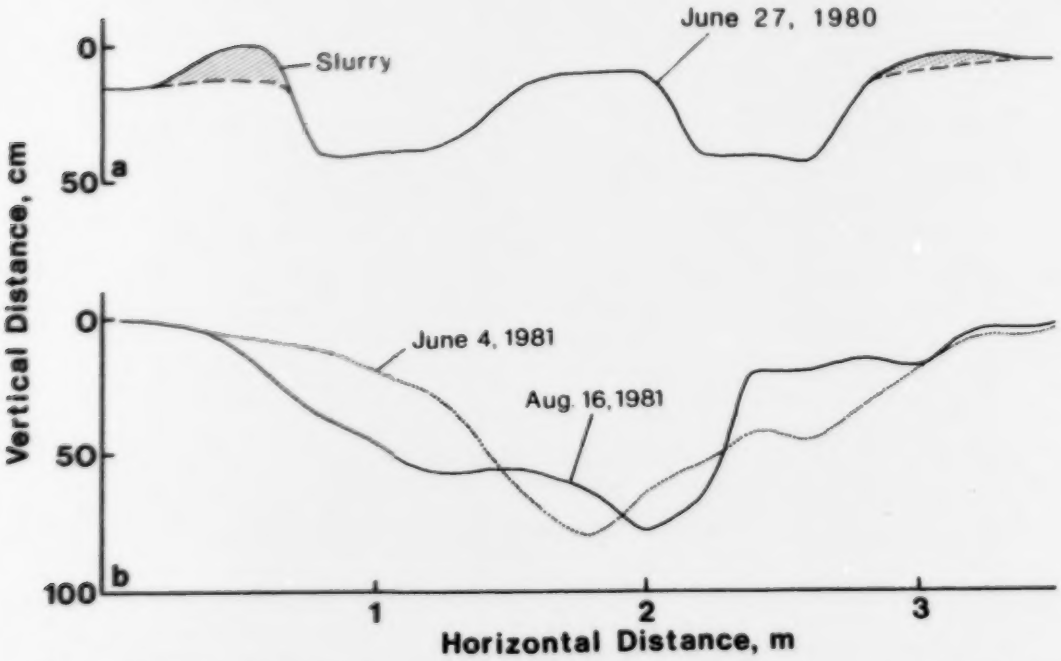

Figure 13 Profiles showing evolution of abandoned ruts on original access route at Nogash site. All profiles are at approximately the 700 m position on profiles in Figure 11.

a. Profile during use of route, June 27, 1980.
b. Profiles on two dates after both the heavy rain of late August 1980 and spring runoff of 1981.

erosion and redeposition of till following a spring runoff.

While downward erosion in general stabilized quickly once till was reached, lateral erosion continued during the summer of 1981. The peat is able to sustain the vertical face forming the side of a rut but is undermined as flowing water removes till laterally. Undermining took place during the summer of 1981 but slumping beginning as tension cracks in the peat gradually produced a stable angle of repose. Profiles across the ruts, showing evolution of the most severely eroded portion of the route, are shown in Figure 13. The rut does not appear to have widened or deepened during the second summer. However this stability will only remain provided continued erosion of slumping peat does not occur.

Lone Gull Site

The deepest rutting at the Lone Gull site took place where the main access route to the drilling area crossed a sedge fen located adjacent to an upland area of extensive bedrock outcrop. This fen derived a summer-long supply of water from a melting snow bank and seepage possibly fed by active layer thaw in bedrock. The route across the fen had to be offset several times (C in Figure 9b) as each new trail was deepened to the point where it became impassible. A drainage path utilizing portions of the resulting ruts was considerably deepened during the same late August rainstorm that affected the Nogash site. Erosion was halted at about the same depth as at Nogash by gravelly outwash. In 1981 little further deepening occurred, although slumping in the same manner as at the Nogash site took place. With the channel gradient across the fen being very low, stabilization of erosion was accomplished by the accumulation of eroded peat in the channel bottom (Figure 14). Because the channel discharges over a nearly level area at the downstream end of the fen, this area may form a base level for erosion and prevent further deepening of the ruts.

Mechanism of rut formation in peat

The strength of peat can be attributed to the same factors that control the strength of a granular soil. Peat has frictional strength when fibres are held in contact, displays tensile strength due to intertwinning of fibres and has a low enough permeability to allow significant excess pore water pressures to develope during rapid loading. Fibric sedge peats grading downward to mesic peats are the dominant peat types at both sites. The peat is covered with a mat, 5-10 cm thick, consisting of living roots and stems. In the severest case, one pass of a vehicle track tears the mat, comminutes the peat and extrudes the resulting slurry, causing a distinct darkening of the ground (Figure 15).

Track passage produces both a shear parallel to the ground surface and a compression perpendicular to it. It is reasonable to assume that shear is most effective in tearing the vegetation mat and comminuting peat, so this action will be most intense when the energy producing a shear deformation is expended on the thinnest thawed zone. Compression is most effective in extruding the peat slurry and raising the pore water pressure and is promoted by increasing depth of thaw. The compression caused by the

Figure 14 Ruts containing sedimented peat slurry at location C in Figure 9b, Lone Gull site.

Figure 15 Trail produced by one pass of tracked vehicle towing drill carrier on peat. Note generation of peat slurry in outside rut, suggesting that the shear accompanying the extra tractive effort required to turn aids generation of the slurry.

application of the weight of the vehicle expells pore water but not quickly enough to allow immediate pressure dissipation. Laboratory loadings of peat samples show that significant pore pressures are maintained long enough to produce a weakening during the entire time the accompanying shear stress is applied by a passing track. Thus the severity of impact will depend not only on the depth of thaw but also on the position of the watertable in the thawed layer.

The profile shown in Figure 11 for June 13 demonstrates the result of traffic on peat early in the thaw. Ruts are produced quickly because of the susceptibility of the thin thawed layer to tearing, comminution and extrusion of the resulting slurry. Passes in rapid succession (at least one per day) result in repeated exposure of the frost table, thereby hastening the thaw and encouraging the formation of a rut. The final 150 m of the June 13 profile, showing rut depth up to 25 cm below the 15 cm deep frost table, was produced in 3 days.

Once the rut reaches a depth of about 30 cm peat slurry begins to accumulate if the rut is not carrying a flow of water. The continued development of the rut then depends on the consistency of the slurry. If drying takes place the remaining slurry strengthens considerably and can resist further development of the rut. The dried slurry becomes almost as insulative as undisturbed peat, judging from thaw depth profiles across abandoned ruts, Figure 16. If the slurry consistency is retained, thermal overturning with each vehicle pass (e.g., Figure 5) will continue to enhance the thaw and rutting will continue until the route becomes impassible. This occurred repeatedly at the Lone Gull site where the main access route crossed the sedge fen fed by summer-long seepage.

For traffic beginning during deeper stages of thaw, the ease with which ruts form depends on the compressibility of the thawed layer. It is likely that saturated peat loaded by a vehicle experiences a rise in pore water pressure great enough to considerably reduce the shear strength of the material. Therefore the position of the watertable in the thawed layer should influence the susceptibility of peat to rutting.

Figure 17 demonstrates the change in compressibility of peat in a fen at the Nogash site where thaw and a dropping water table occurred more or less simultaneously over a large part of the summer. The pressures graphed on the vertical axes were recorded as a vehicle was repeatedly driven over buried, water-filled balloon pressure sensors. Each test commenced on undisturbed terrain. In general, the pressure readings decrease with successive passes for each of the tests. With each successive pass the peat is stiffened and shields the pressure sensors from more and more of the load. More importantly, the lowering of the watertable between tests appears to produce the same result, i.e. less and less compression takes place over each of the three successive tests.

The direct measurement of shear strength in peat verifies that an increase in shear strength is associated with a decrease in compressibility. The curves in Figure 18 were derived from shear strengths measured with a Geonor hand-operated vane shear device at locations 10 m apart along the valley at the Nogash site. Each point defining the curves represents the average of 30 measurements. The curve for 1980 spans the same time period

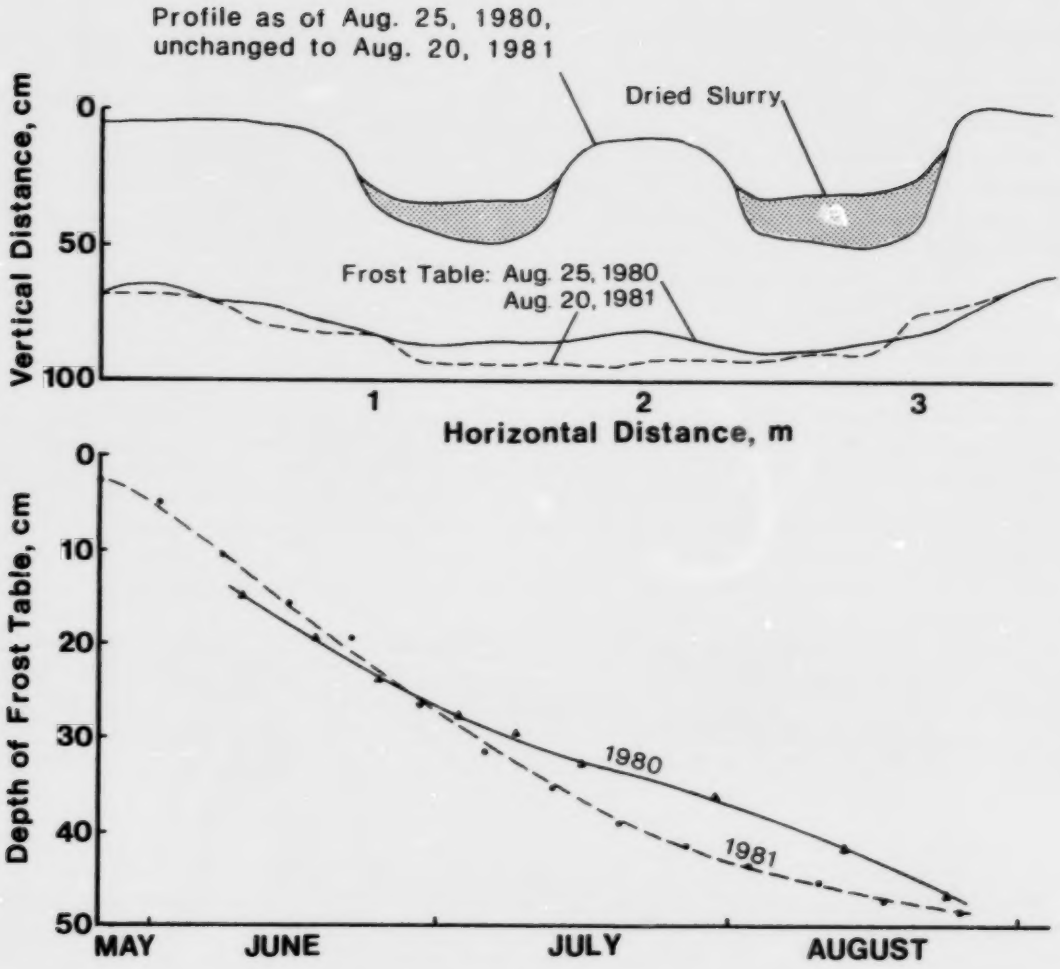

Figure 16 Profile across abandoned route in peat at a location not eroded by runoff. Graph below compares depth of frost table between 1980 and 1981 at a site in peat within a few meters of the profile. It suggests that slightly deeper thaw under the ruts in 1981 is partly a result of climatic variation rather than reduction of insulation.

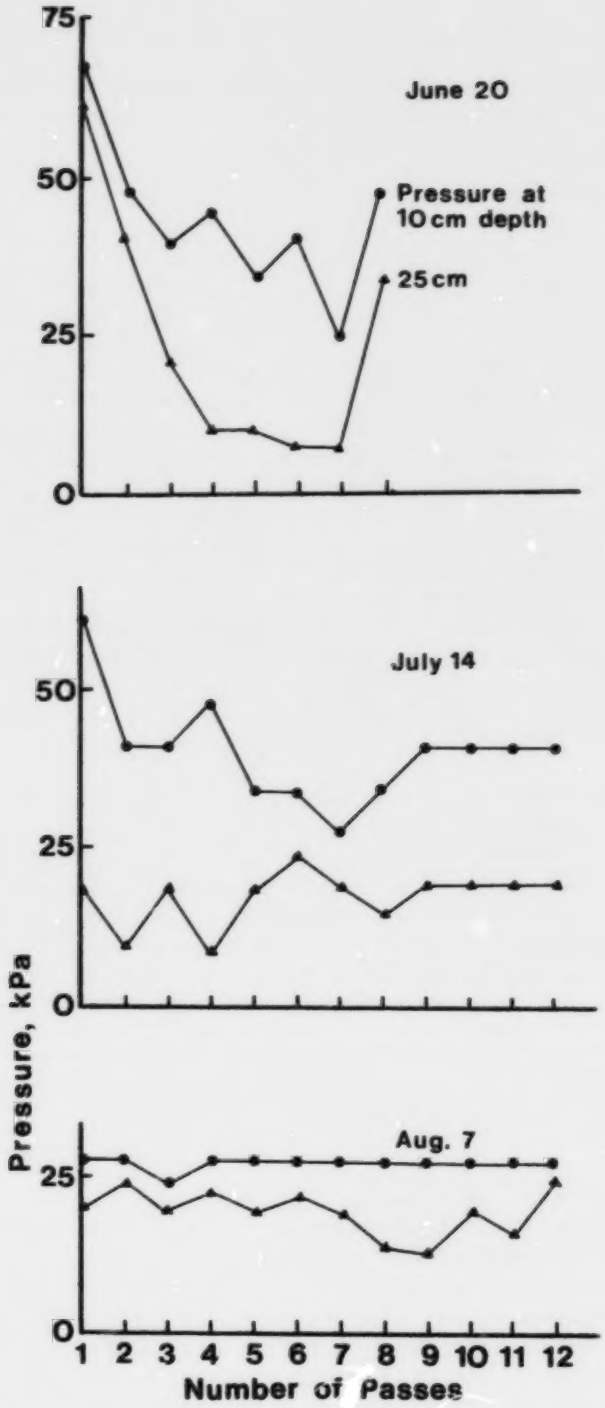

Figure 17 Bearing pressures measured beneath Bombardier Muskeg Tractor in peat during successive passes. Tests carried out in 1980.

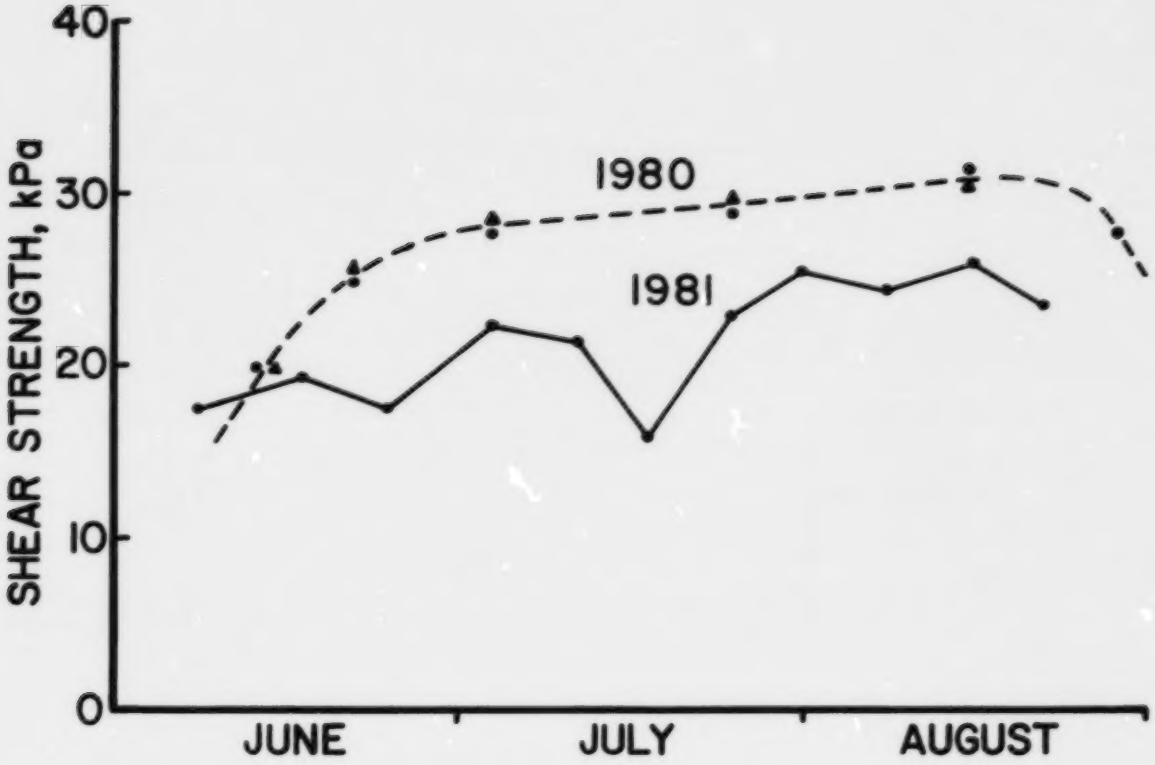

Figure 18 Shear strength of peat in a fen at the Nogash site for summers of 1980 and 1981.

as the compression tests.

The influence of increasing shear strength in peat is seen in the profile of the new access route that was established at the Nogash site in mid-July (Figure 19). This route crosses part of the same fen traversed by the last 300 m of the abandoned route and experienced a similar volume of traffic over the next month. Rut depth on this new route in peat nowhere exceeded 10 cm.

Variability in Susceptibility to Rutting

The rapid increase in shear strength of peat indicated during June, 1980 in Figure 18 suggests that time elapsed after the onset of thaw may offer a reliable criterion for deciding when traffic on peat will carry the minimum risk of rut formation. However, this conclusion is drawn from a summer with a rainfall history permitting a more or less steady drop in water table level during June. Comparison of the rainfall records for the summers of 1980 and 1981 at the Nogash site show that, for the thaw season up to the end of June, 8 mm and 75 mm fell respectively in 1980 and 1981. The effect of this variation in rainfall is reflected in Figure 20, a set of watertable measurements selected as representative of measurements taken in several standpipes in fens at the Nogash site. Waterlevels in 1981 remained at or near the surface of the peat for considerably longer than in 1980. The influence of these higher 1981 water levels on shear strength is shown by the solid curve in Figure 18.

A load cell was used to determine the force exerted by the vehicle in towing a track-mounted drill trailer on level ground. This test indicated that a shear stress of up to 10 kPa was produced by the vehicle tracks. While this value is below those exhibited for most of the summer in Figure 18, the weakening influence of increased pore water pressures indiced beneath an overriding track may reduce the peat strength to a value below the stresses exerted by the track. Also the considerable variation in peat strengths between 1980 and 1981 suggest that variations in rainfall from year to year can play an important part in determining sensitivity to disturbance.

Regulating Traffic on Peat

The objective of studying peat strength is to choose a terrain condition which will ensure that disturbance will not lead to continued degradation once a route is abandoned. Preferably ground layer vegetation would remain more or less intact and capable of regrowth. From the foregoing discussion it is apparent that the inconsistency of the summer rainfall pattern prevents a reliable prediction of peat strength being made. Therefore selecting an elapsed time after the onset of thaw does not offer a reliable criterion for the decision to permit vehicle traffic. The choice remains to decide what amount of traffic under any terrain condition can be tolerated with a reasonable assurance that some vegetation will remain.

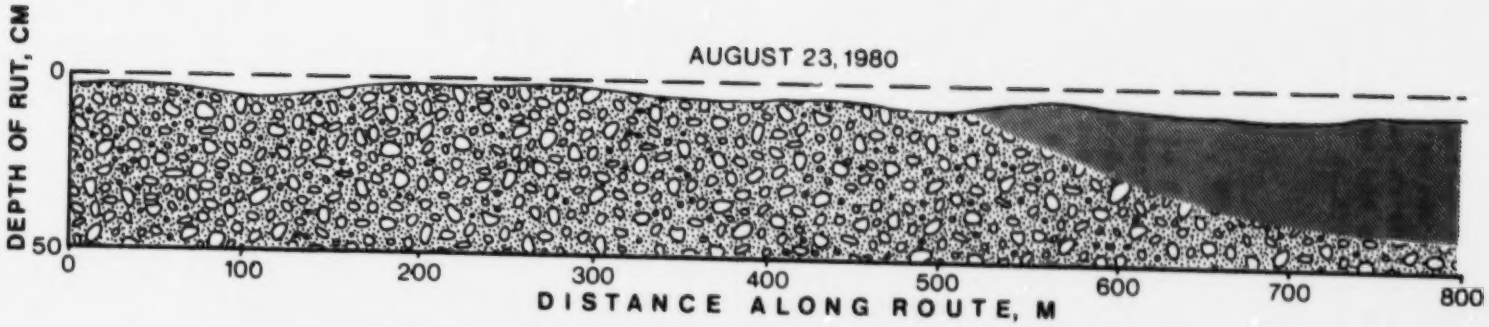

Figure 19 Longitudinal profile of new access route established in mid-July at the Nogash site (route B in Figure 9a).

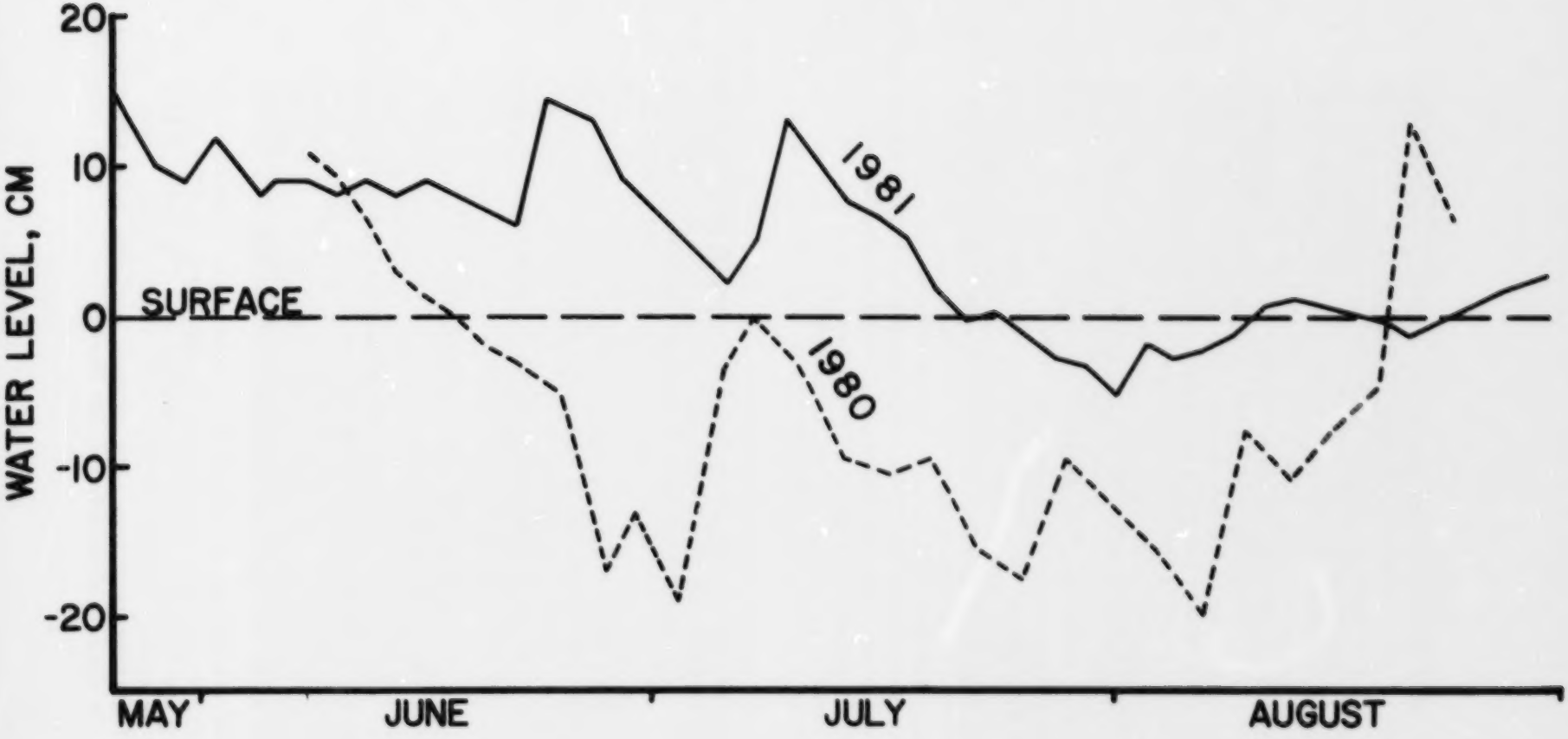

Figure 20 Water table levels measured during the summer of 1980 and 1981 in one of several standpipes selected as representative of fens at the Nogash site.

The chief physical requirement for revegetation on peat is preservation of enough of the surface mat to allow continued growth of the disturbed vegetation (Figure 21 & 22). The increase in stiffness and shear strength that accompanies drying also prevents the formation of the peat slurry and allows only a slight compression under repeated passes (e.g., Figure 19). With these conditions the living mat is not destroyed and recovery will begin as soon as traffic ceases. On the other hand the saturated condition associated with the early stages of thaw or heavy rains promotes formation of the peat slurry. Living vegetation as well as peat fibres are shreaded, leaving little plant material for continued growth. A further danger is the erodibility of the slurry. Should flowing water have access to the slurry, erosion will retard recovery and tend toward the condition reached by the original main access route at the Nogash site.

The ease with which material is removed by erosion depends on how much the original fabric of the peat is altered. An attempt to determine the rate of degradation was carried out by separating the coarse and fine fractions of undisturbed peat and slurry samples collected from vehicle trails and adjacent undisturbed ground. A 5 mm sieve was used to make the coarse-fine split, the choice based only on the impression gained in the field that the generated slurry would readily pass this size of mesh. Only a modest increase in the fine fraction over that present in undisturbed peat takes place after one pass (Figure 23). At this stage most of the original intertwining fabric is still intact and the peat has lost little of its tensile strength. By six passes most of the peat has been reduced to the fine fraction and retains little tensile strength.

Because slurries are produced by a single pass (e.g., Figure 15) and the sieve analysis shows only a small increase in the fine fraction for one pass, it is probable that the slurry originates as a pre-existing fine fraction. This fraction is then added to by the comminution of coarser fibres during succeeding passes. It is hypothesized that the slurry is initially formed by the flushing of the fine fraction from the network of coarse fibres through the living vegetation mat. This flushing is caused by the flow of pore water to the surface induced by loading from a passing vehicle. Therefore a high water table favours this flushing. Continued traffic not only produces more slurry but also destroys the mat, reducing the potential for revegetation.

The conditions required for the generation of a slurry (i.e., watertable at or near the peat surface) can exist at any time during the summer. However, the sieve analysis suggests that one pass will not significantly alter the peat fabric. Enough living material will be left intact to initiate recovery and resist erosion.

Influence of Track Design

Track design may determine how rapidly the vegetation mat is destroyed. Two characteristics of tracks may be important in this regard: relief of the track surface and lateral flexibility. The track design on the Bombardier Muskeg Tractor incorporates steel channel cross links as the means of gaining traction. The channel openings face the ground and are about 2 cm deep. Crosslinks on the Muskeg Carrier were considerably deeper

Figure 21 Ruts on original main access route as they appeared on June 4, 1981 approximately one year after abandonment.

Figure 22 Same location as Figure 21 on August 22, 1981. Note recovery of sedges along sides and center of trail where original vegetation was not destroyed.

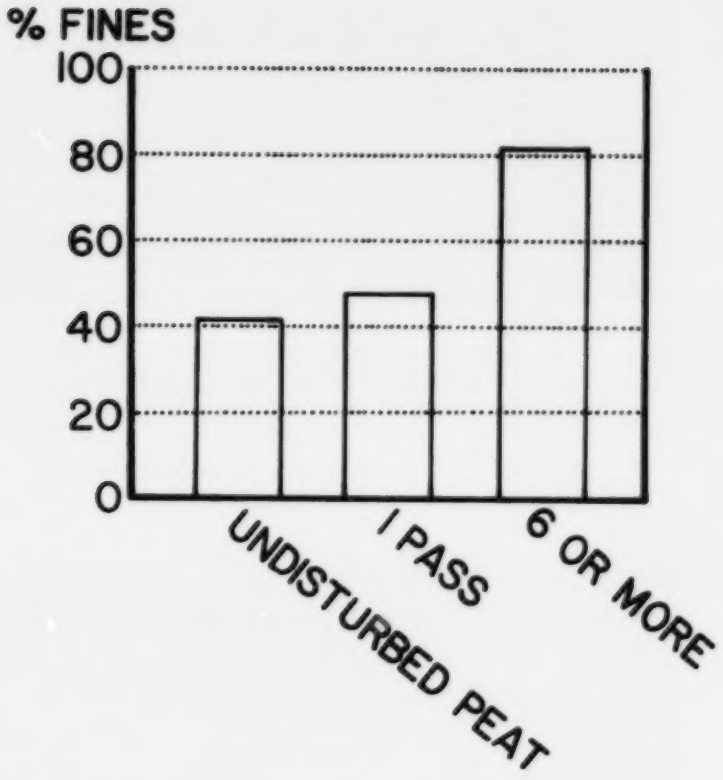

Figure 23 Bar graph showing increase in amount of fine fraction ($\leq$ 5 mm) in peat slurry after given amounts of traffic.

(approx. 5 cm) and the channels filled with a hard rubber. A direct comparison of the effect of the loaded vehicles on the vegetation mat was not made. However, the greater relief on the Muskeg Carrier track probably results in tearing of the mat to a corresponding greater depth, causing a more rapid degradation of the mat. No advantage in traction on peat was noted with the higher relief track, both models becoming immobilized by terrains too soft to afford the required shear strength.

Lateral flexibility of a track controls the ease with which a rut is incized. Both models of Bombardier are relatively rigid due to the support offered by two parallel rows of wheels per track. Therefore a considerable amount of the vehicle weight is supported by the edges of the track, favouring an abrupt down-cutting in highly compressible materials. Tracks of the same width but with only one row of wheels were seen in use on sedge meadows in the Churchill, Manitoba area. While these vehicles were engaged only in transport of tourists, routes used on a one round trip per day basis for several weeks showed a rut having a dish-shaped cross section. While this design may reduce the speed with which the mat is destroyed, loss of traction may result due to the small amount of the vehicle weight supported by the track edges.

Mechanism of rut formation in till

The mechanical properties of till are also dependent on hydrologic conditions. However, till occupies a wider variety of hydrologic environments than peat. Depending on the availability of water, till may remain susceptible to liquifaction all summer or harden quickly shortly after the onset of thaw.

The well-graded texture of the till at the Nogash and Lone Gull sites is essentially responsible for its variable behavior. The following percentages of clay, silt, and sand, respectively are typical: 10%, 30%, 60%. With this grading, the permeability remains similar to a pure clay. Therefore when a saturated till is compressed, drainage is not readily accomplished and the pore water pressure consequently rises. The negligible cohesion in the saturated state permits ready liquifaction and a vehicle or trailer will experience a bearing capacity failure. On the other hand, if the till dries, enough clay is present to produce a cementation and the material acquires a shear strength far in excess of that necessary to support off-road vehicles.

Segregated ice is common in the tills and on melting provides most of the excess water that makes the material susceptible to liquification. Where the organic layer is thin, ice lenses up to 5 cm thick are often present in the top 30 cm of the till. Otherwise lenses up to 2 cm thick are common on the underside of boulders. In several profiles the frozen till matrix shows a consistent decrease in water content with depth to the maximum depth sampled. Bulk water contents of 30-40% (by weight) near the surface decrease to as low as 6% at the depth of 60 cm, approximately half the depth of the active layer. Deeper sampling by other workers has shown a reversal in this trend as the base of the active layer is reached, both in the Mackenzie Delta area (Mackay, 1980) and Keewatin (Egginton, personal communication, 1983).

Deep ruts form during one pass as a result of liquifaction followed by bearing capacity failure (Figure 24). The wheel-mounted trailer produced ruts in this manner frequently, the track-mounted trailer only on rare occasions (Figure 24). No rut in till was deepened by erosion, mainly because areas likely to have a surface water flow are confined to areas with a peat cover.

Revegetation after rutting must take place by recolonization of a bare till surface. Like peat, till carries a surface mat of living vegetation. Where deep liquifaction takes place the mat is usually preserved by simply being forced downward under the track. The effect of prolonged traffic depends on the state of the thaw and the actual vegetation cover. Travel early in the thaw causes a comminution and extrusion of the surface mat, quickly resulting in a bare till trail (Figure 25). However, on well drained till, deepening from continued use is usually prevented by the cobble and boulder content. For traffic beginning after the onset of thaw on well-drained till the surface mat will either wear gradually away or even undergoe only a slight compression (Figure 26 & 27). Revegetation will simply depend on how much of the mat and organic soil is preserved. Where compression is the only disturbance, regrowth will begin the same summer, otherwise recolonization from adjoining vegetation must take place.

Active Layer Hydrology in Till

In the preceding description the essential behavior of till has been presented but without any discussion of the hydrologic environments claimed to influence till behavior. During the 1980 field season it was noticed that till slopes below bedrock outcrops seemed to display the liquifaction characteristic for a longer period than slopes or hilltops where outcrops did not occur. Considering that the active layer in bedrock is approximately 3 times the depth in till, bedrock outcrops, with ice-filled cracks and fissures, may serve as reservoirs of active layer melt water. This water would in turn supply seepage to the till active layer and maintain saturation. Water levels in bedrock openings were monitored and noted to decline steadily over most of the summer. Therefore a water source is present and active layer seepage apparently provides the only exit.

To investigate this hypothesis, water levels were monitored on two slopes apparently having the contrasting conditions described above. The slope capped by the outcrop is referred to as the "wet" slope and the slope capped by a till-covered hilltop, the "dry" slope. On each slope six standpipes were installed along a transect between the top and the shore of a lake forming the base of both slopes (Figure 28).

Figure 29 shows water level records from a selction of standpipes on the wet and dry slopes. All records show a common general trend characterized by a declining water level until late July followed by a rise over the next month. This general pattern was also shown by standpipe records from the Lone Gull site taken in 1980 (Ferris, 1980) and has been observed in bulldozed till on a 7 degree slope near Inuvik, Northwest Territories (Lissey, 1975). Superimposed on all the Nogash records is an

Figure 24 Ruts in poorly drained till after one pass.

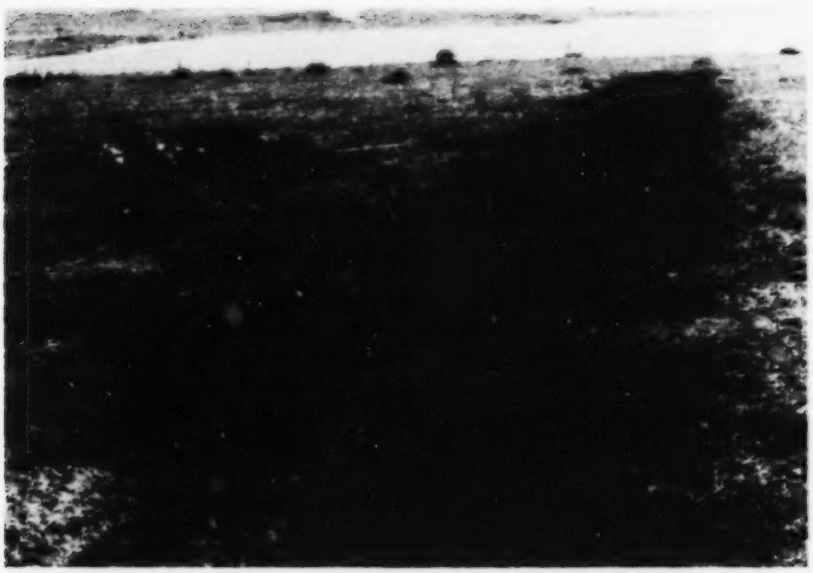

Figure 25 Original access route on well-drained till at Nogash site. June 17, 1980. At this location traffic coincided with beginning of thaw.

Figure 26 Original access route on well-drained till at Nogash site. At this location traffic began approximately 20 days after the beginning of thaw. Photo June 3, 1981.

Figure 27 Same location as Figure 26 on August 22, 1981.

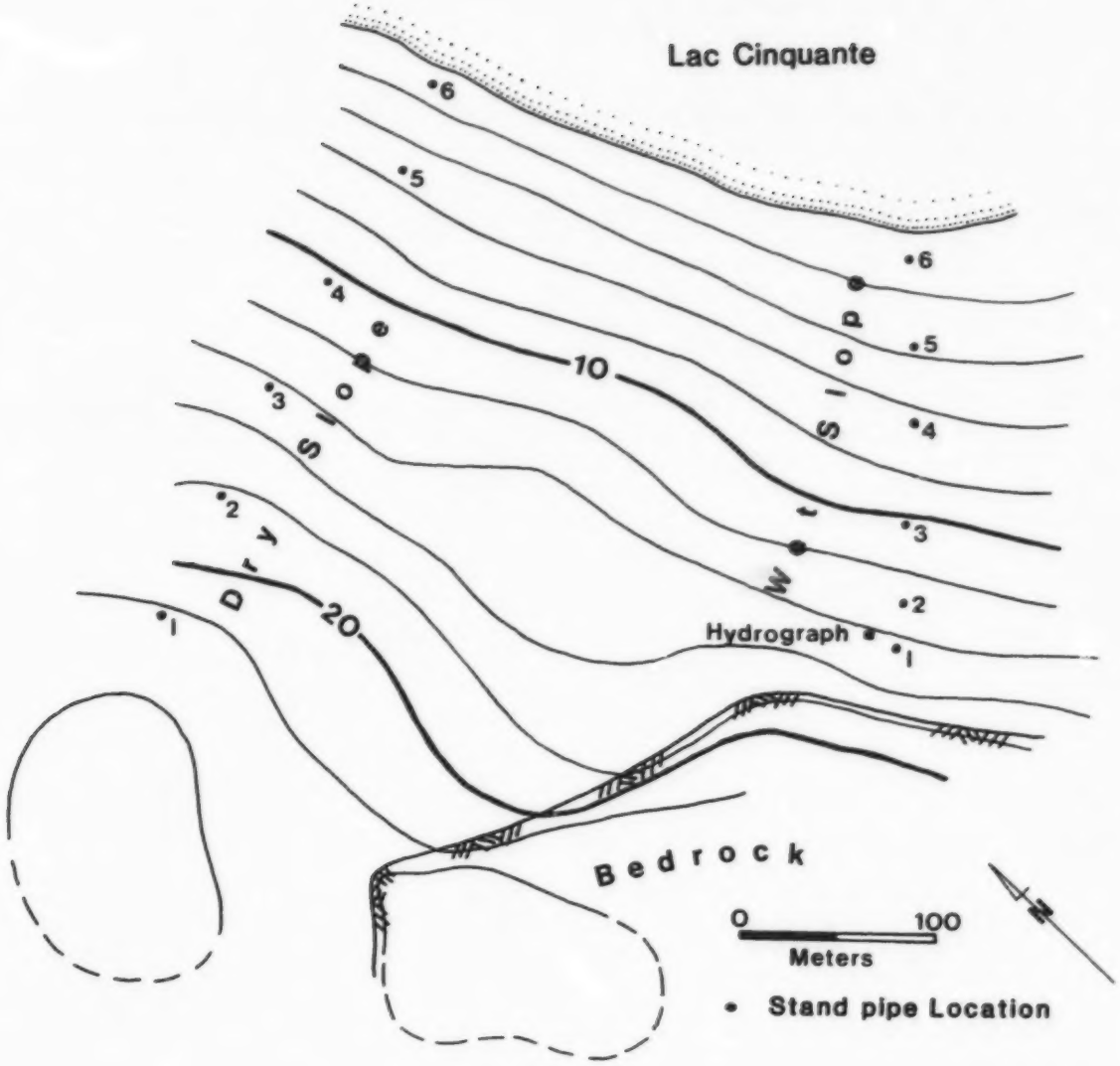

Figure 28 Topograhic map of area used to study active layer hydrology at Nogash site. Contour interval is 2 m.

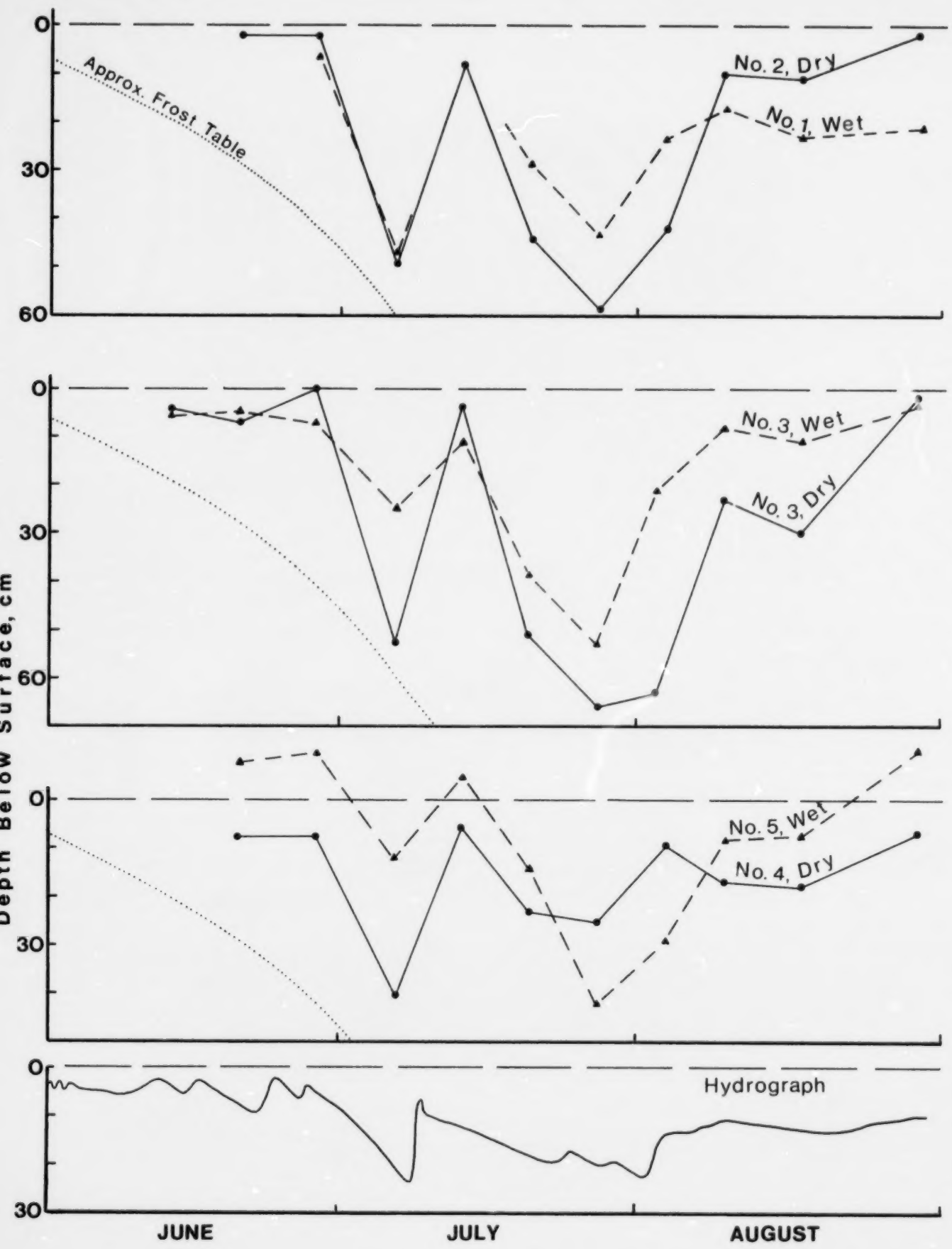

Figure 29 Watertable levels for selected standpipes on wet and dry slopes.

abrupt rise in early July which is coincident with the heaviest rainfall of the 1981 summer. While measurements were taken only about once a week, a comparison with a continuous hydrograph taken near the top of the wet slope shows that the weekly measurements do reflect the general character of water level variation. The general August rise of the water table may reflect the encounter, by the thaw front, of the previously mentioned ice-enriched zone at the bottom of the active layer.

Comparison of the records for the wet and dry slopes does not reveal any striking contrast in behavior, despite the expectation that water levels might remain high on the wet slope. A consideration of Darcy's equation shows that the higher discharge presumed to occur through the thawed zone of the wet slope, rather than being accomodated by a greater cross sectional area, could be accomodated by a greater hydraulic conductivity or hydraulic gradient.

Settlement of the till surface on both slopes was measured by monitoring changes in surface elevation relative to a string supported by rods driven well into permafrost. The settlement records are plotted in Figure 30. The overall settlement on both slopes at the end of August was equal but most of the settlement on the dry slope occurred during June while less than half the total on the wet slope took place during this time. If the measured settlement is an expression of consolidation then the slowness of consolidation on the wet slope may be caused by seepage pressures maintained by groundwater flow from upslope. It is hypothesized that water-filled cavities formed by melting of ice lenses effectively increase the hydraulic conductivity parallel to the slope and that the collapse of these cavities is slowed by seepage from upslope.

To verify the effect of seepage on consolidation, a continuous water supply was arranged to produce a variety of hydraulic gradients across a thawed till sample in a 10 cm diameter permeameter. While it was not possible to grow ice lenses of the size present in natural till profiles, some sample dilation was produced by the growth of fine lenses. It was possible to control the amount of settlement by the application of different hydraulic heads. Figure 31, a summary of the results of the permeameter tests, shows that for an average hydraulic gradient across the sample of one, no consolidation took place during tests lasting 1 day.

In a slope composed of thawing till, water movement will occur in response to consolidation and downhill seepage. Initially the hydraulic gradient due to consolidation may be approximately 1 but will decrease as water is expelled upwards and consolidation proceeds. If expelled water can be replaced by water under a high enough pressure, a high hydraulic gradient will be maintained and consolidation will be slowed. A given water-filled cavity would be capable of introducing water at increasingly high pressure heads downslope (Figure 32) and so provide a high enough pressure locally to retard consolidation. This would also promote liquification should a load be applied to the surface over one of these high vertical gradient zones.

In order for consolidation to be retarded, a continuous supply of water must be available to maintain an upward seepage. This supply of water may be made available by flow between water-filled cavities, parallel to the

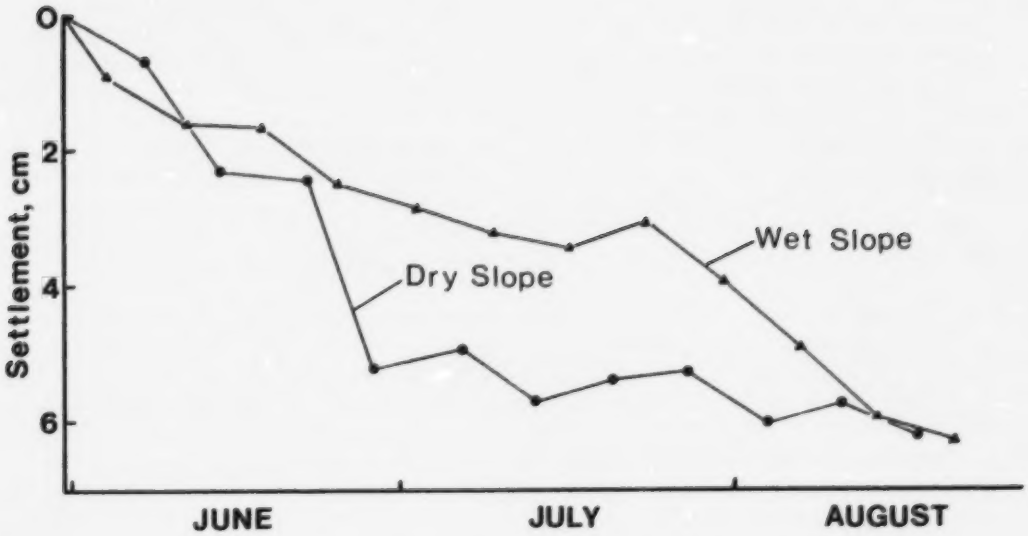

Figure 30 Settlement of till surface on wet and dry slopes, summer 1981.

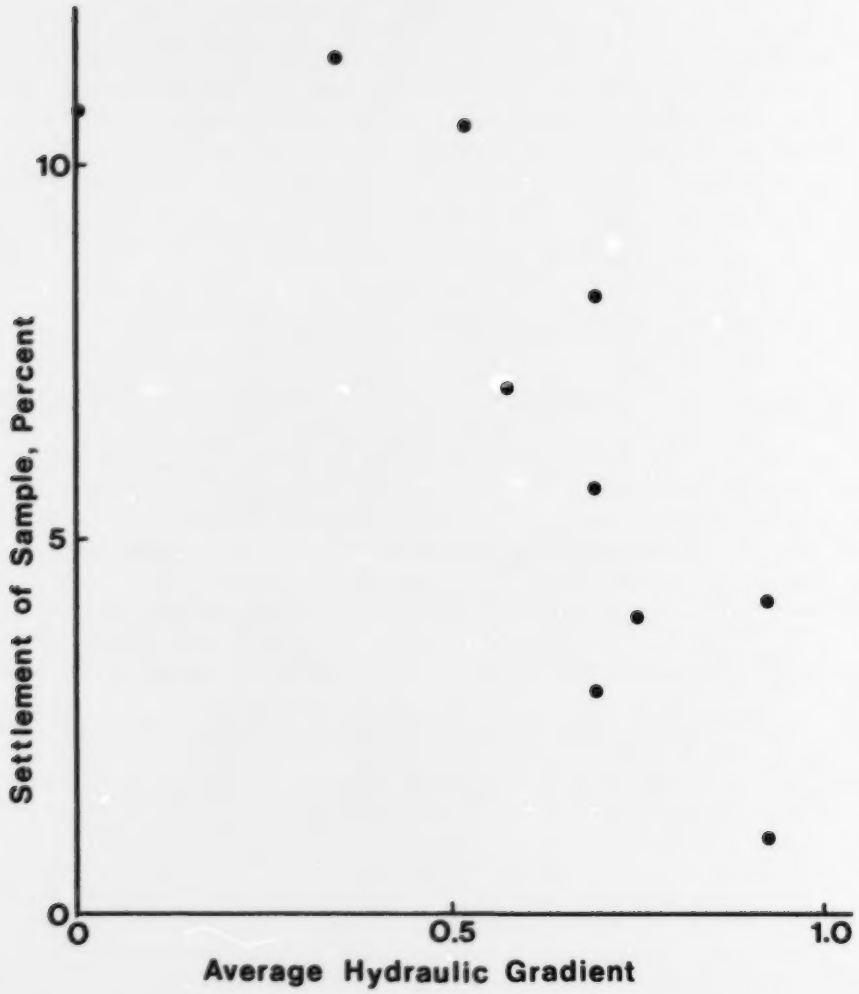

Figure 31 Consolidation experienced by thawed till under varying hydraulic gradients across an 11 cm high sample in a 10 cm diameter permeameter.

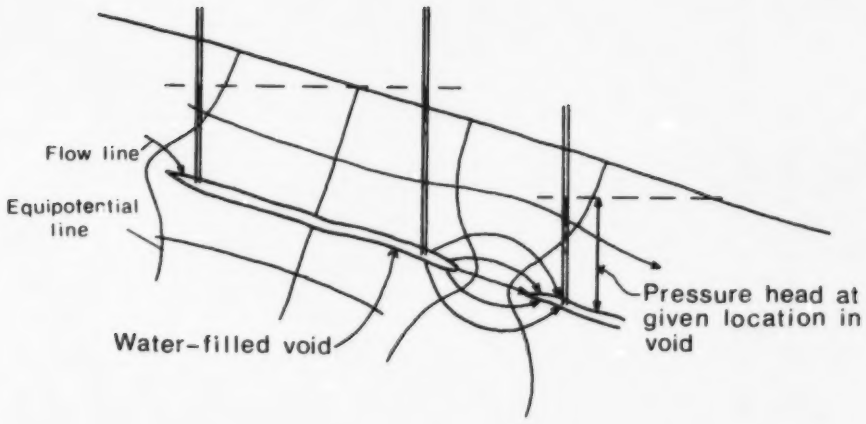

Figure 32 Hypothetical cross-section of a sloping active layer in till showing water-filled voids formed by melting of ice lenses. Dashed lines show total hydraulic head in each void.

slope. Because the hydraulic gradient between cavities would be much higher than the average gradient dictation by a uniform slope (Figure 32), the effective hydraulic conductivity parallel to the slope may be 1, 2, or even 3 orders of magnitude higher than the hydraulic conductivity perpendicular to the slope. In this case a slope length equal to the active layer thickness multiplied by this factor could be supplied with seepage water from an outcrop. Slopes up to 100's of meters below outcrops could be effected by "wet slope" conditions.

The distinction between so called wet and dry slopes is tentative and requires substantiation. The assumed presence of lens-shaped cavities to carry water seems reasonable in view of rapid seepage observed in pits at the Nogash site and elsewhere in District of Keewatin (Egginton, personal communication, 1983). Beside the terrain disturbance point of view, distinguishing these two environments has general geotechnical implications. Interruption of slope seepage by any structure such as a road or building foundation may cause ponding. In selecting till as a construction material, recognizing wet and dry slopes may also aid in avoiding extra effort in producing material with the required moisture-density relation.

Terrain Disturbance Under Supervised Vehicle Use

Trails

Severe disturbance, represented either by ruts deep enough to require abandonment or ruts deepened by erosion, was produced at both study sites. While such occurrences were not typical of the overall reaction to vehicle use, such levels of impact are unacceptable under present land use regulations. In view of these results, vehicle use during the second summer at the Nogash site was limited by the company to the single trip necessary to move a drill rig between any two drilling sites. As a result, disturbance severe enough to allow erosion was never produced.

In an attempt to give a more representative documentation of the vehicle and drilling impact to be expected under a single trip restriction, vehicle trails and drill sites made during 1981 were rated according to a four-fold classification of disturbance. In the case of a trail, the classification is based on the condition of ground layer vegetation and the degree of rut development. For a drill site, condition of vegetation only was evaluated. The four categories are as follows:

Level 1 - Track imprinted in vegetation but no tearing of ground layer vegetation or cutting of soil.

Level 2 - Patches of vegetation have been stripped away to reveal dark brown peat or light coloured mineral soil, hummocks sliced but rutting is otherwise restricted to compression of soil; peat slurry may be present but vegetation is mostly in place and visible.

Level 3 - Most vegetation has been stripped away or peat slurry well developed with vegetation incorporated in the slurry; a distinct rut has formed (i.e., an

incised depression in rather than compression of the soil) but is less than 20 cm deep.

Level 4 - Peat or till has been squeezed to the sides of the trail, leaving a distinct rut; vegetation may survive but has been completely incorporated in the slurry or buried by extruded till.

The trail produced by each drill move was paced and divided into segments assigned to one of the three terrain types (i.e., well-drained till, poorly drained till, or peat). At the same time these segments were classified according to the four levels of disturbance. Using this data, a series of graphs were prepared illustrating the changes in the susceptibility to disturbance with time. For each terrain type, the length of trail exhibiting a given level of disturbance for weekly periods was plotted as a proportion of the total distance travelled over that terrain type.

During the summer of 1981 approximately 40 moves of the carrier-mounted drills were made for a total distance of approximately 60 km. This gives a considerable sampling of the terrain response to vehicle and drill movement. Because each terrain type is not equally represented on each move the data are not strictly suitable for a statistical analysis. However, enough information is present to judge how the terrain types react over the summer.

Figure 33 shows the extent of level 2 impact. Missing columns indicate that the associated terrain type was not traversed during that week. Most apparent is the lack of any large variation in the amount of level 2 impact. Three periods of rainfall, yielding from 30 to 60 mm each, occurred in late June, early July and early August but are not reflected as increases in sensitivity at this level. Hence the amount of level 2 impact recorded is probably unavoidable and represents the minimum disturbance that is likely for each terrain type, irrespective of moisture conditions.

The graphs of higher level disturbance (Figure 34) show a distinct change over the summer. The steady increase followed by a sudden decrease in disturbance at the end of June on well and poorly drained till suggests that depth of thaw is a controlling factor. By the end of June the thaw has penetrated through the zone of water enrichment caused by near-surface ice segregation. Once the base of this zone is reached, the supply of excess water dervied from thawing ice lenses is reduced. Thereafter susceptibility of liquifaction decreased because consolidation is able to take place as the previous continuous supply of meltwater decrease. Measurements of frozen water content on poor and well-drained till were only made in a few locations but what data is available suggests that both types of till show the same concentration of moisture as ice in the upper 30-50 cm. Because poorly-drained till usually coincides with "wet slope" conditions, the pronounced increase in sensitivity on poorly-drained till may reflect the influence of the hypothesized wet slope seepage on consolidation.

Rainfall does not appear to be capable of significantly increasing the sensitivity of till to disturbance. While the watertable can be raised, as indicated in Figure 29, no associated reversal in settlement is seen in

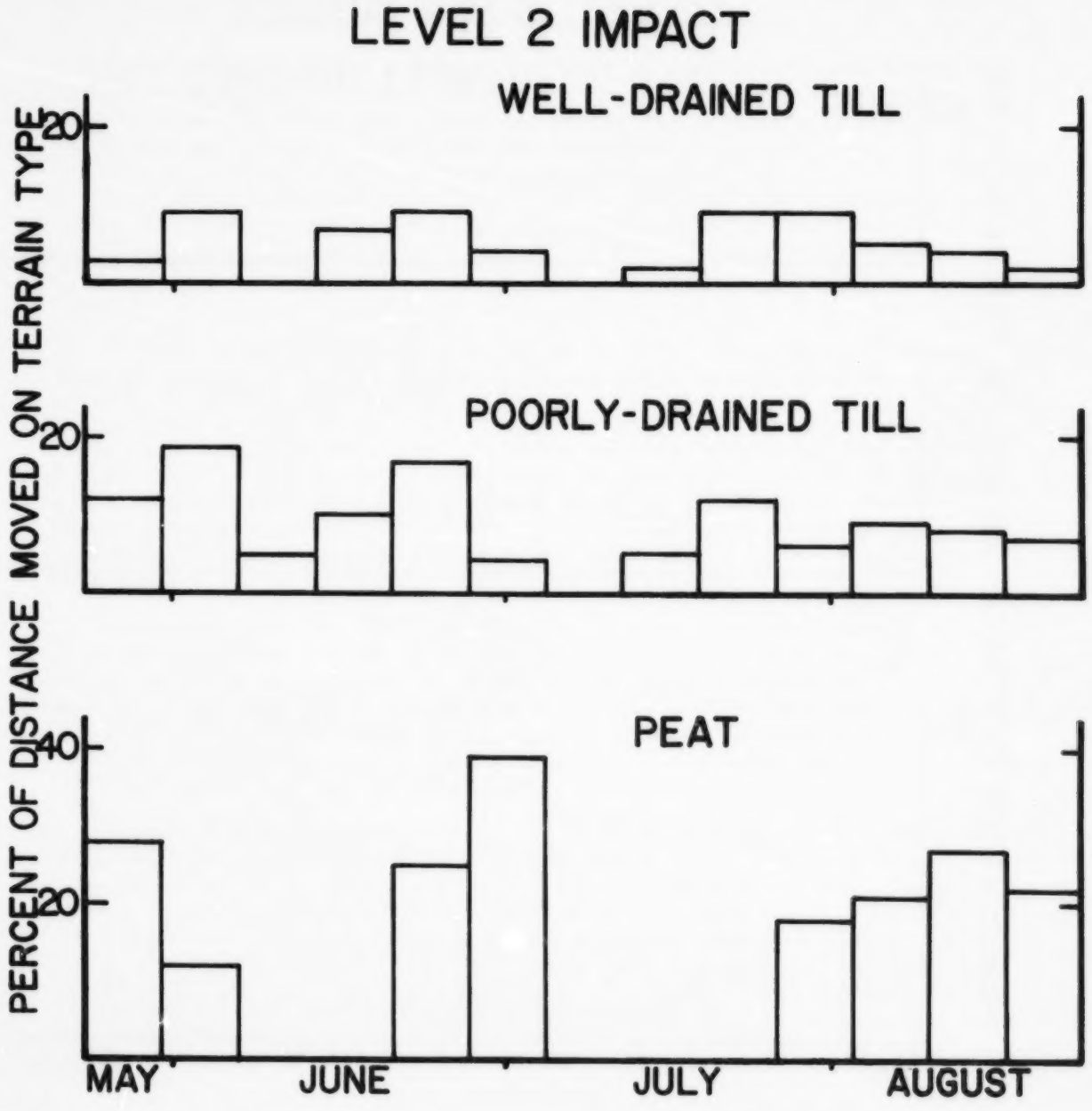

Figure 33 Record of level 2 impact produced during drill moves in 1981 at the Nogash site. Each bar represents the amount of level 2 impact produced during one week as a percentage of the total distance moved on a given terrain type during that week. Absence of a bar indicates that no drill moves took place on a given terrain type during that week.

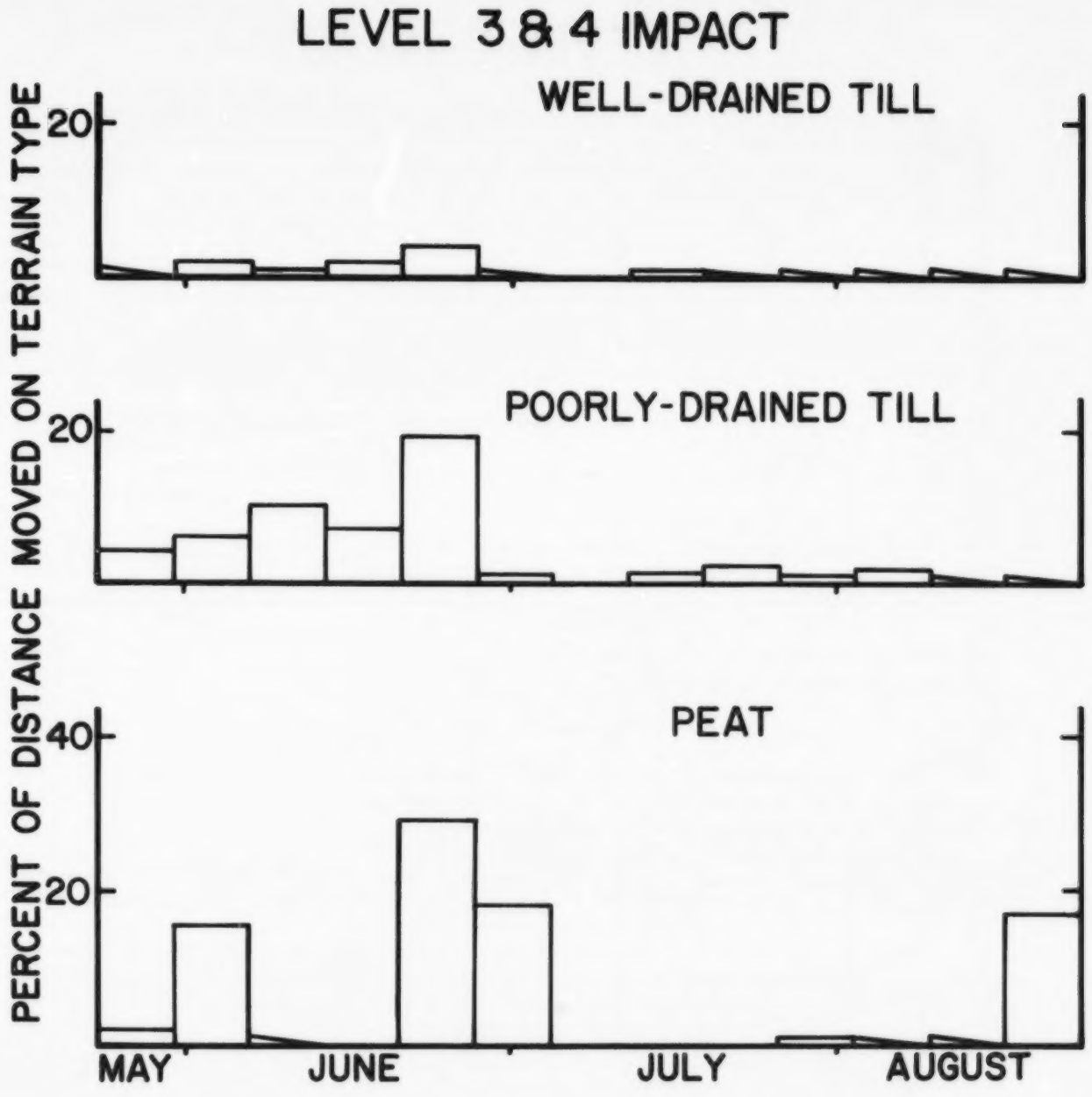

Figure 34 Record similar to Figure 33 for level 3 and 4 impact. Triangles indicate that drill moves took place but no impact at this level occurred.

Figure 30. Furthermore, Figure 35 shows records of dry bulk density for the top 10 cm of till taken from three localities at the Nogash site. Apart from an initial increase reflecting consolidation, very little variation is seen. In general it seems reasonable to conclude that the sensitivity of till is controlled by thaw and drainage. It is not reversed but at worst only prolonged by rainfall.

Like till, peat shows a general tendency to densify over the summer but is more influenced by surface water conditions. While the disturbance analysis for peat lacks data from four weeks, two reversals in sensitivity can be picked out. The data lacks the completeness to show a definite correlation with rainfall. However, the demonstrated influence of water levels on peat mechanical behavior implies that variations in water levels over the summer are responsible for this variability in sensitivity.

Drill Sites

The impact classification was applied to drill sites by establishing a grid over each site and assigning an impact level to each grid point. This map could then be contoured and an area for any given level of impact calculated. Only drill sites on poorly drained till were numerous enough to provide a thorough sampling of terrain response throughout the summer. Figure 36 shows the amount of level 3 and 4 impact and occupation interval for each drill site in poorly drained till. The change in the amount of disturbance over the summer differs from that for trail disturbance in that the greatest amount of disturbance occurs immediately after the onset of thaw (latest May for 1981) and then falls off rapidly with time.

The explanation for the difference in terrain behavior probably lies with the operating routine about the drill site. In 1981 a determined effort was made to position the drill carrier with a minimum of manoeuvering. A straight course was maintained on the final approach to the drilling position and so drill carrier movement accounts for little of the site disturbance. Subsequent movement of the tractor during drill site chores produces most of the disturbance.

Because the bearing pressure of the tractor is almost half that of the drill carrier, bearing capacity failures rarely occur. It must be concluded that track shearing produces most of the disturbance. Small radius turns are common about the drill site and would tend to emphasize the shearing effect. The disturbance is greatest immediately after the onset of thaw because the shearing is confined to a thin zone of thaw. As the thawed zone thickens, the shearing is distributed over a larger volume and so the surface mainfestation decreases.

Conclusions

The measures necessary to ensure that an unacceptable level of disturbance is avoided depends on the level chosen. Land use inspectors responsible for operations in central Keewatin generally consider level 3 and 4 of the previously described classification as unacceptable for the peat and till terrain of central Keewatin. The present study shows that

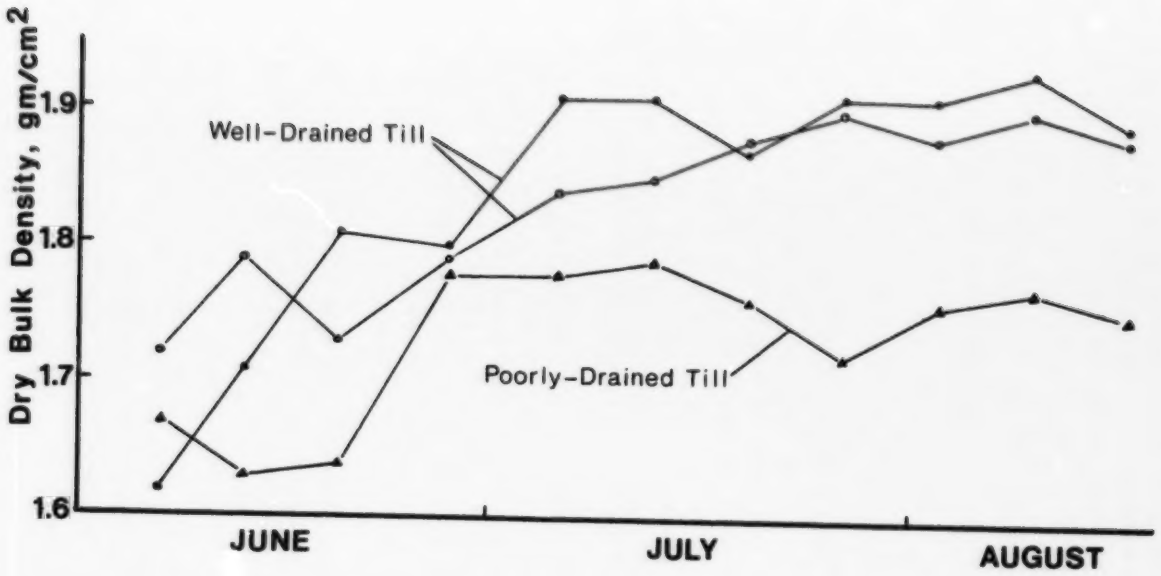

Figure 35 Change in dry bulk density of the upper 10 cm in till at three localities at the Nogash site, 1981.

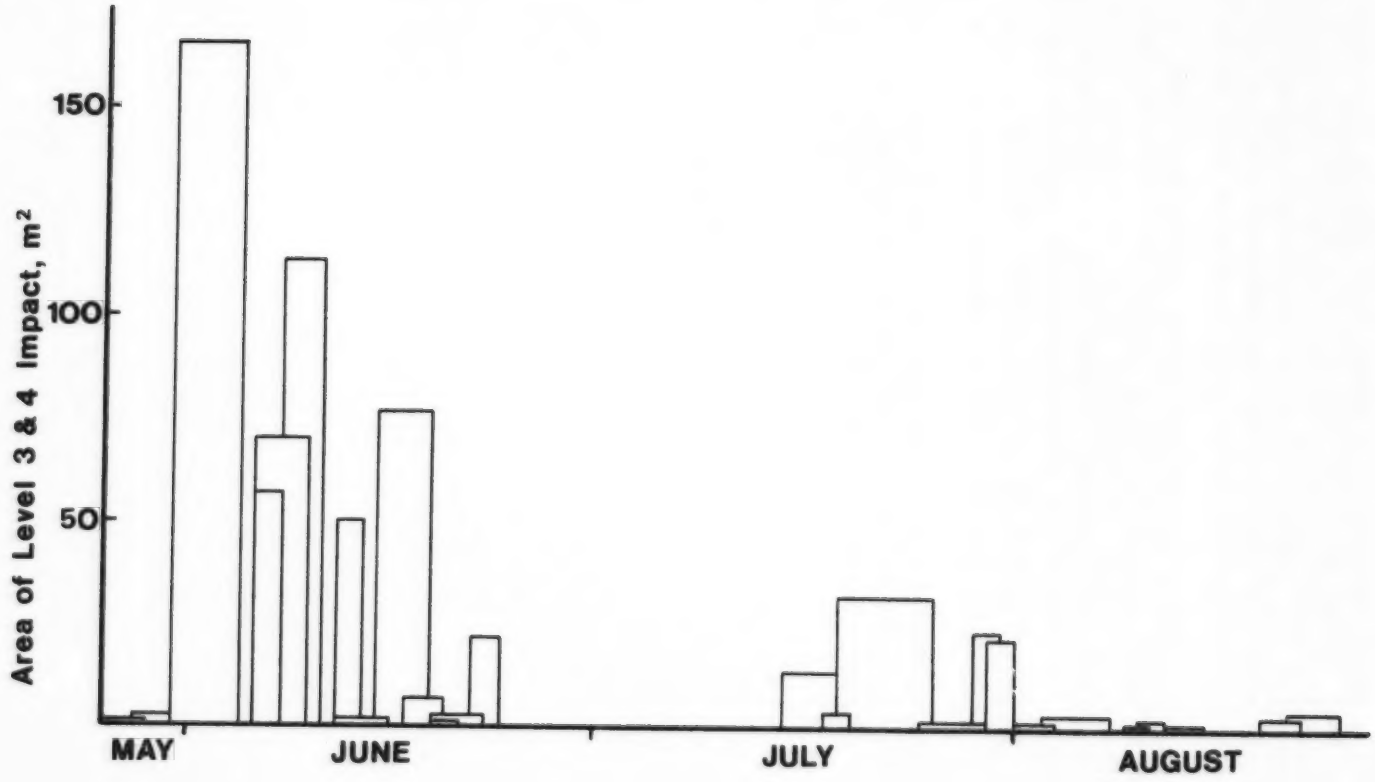

Figure 36 Record of level 3 and 4 impact of drill sites in poorly drained till for 1981. The height of each bar represents the surface area of impact and the width represents the time each drill site was occupied.

these levels are frequently reached during identifiable periods exhibiting sensitive terrain conditons. On the other hand the vehicle use supervision exercised by the operator during the second summer demonstrated that drill move supervision as a formal part of the exploration program eliminated non-recoverable disturbance. A slight additional effort directed at avoiding poorly-drained till areas early in the the thaw and peat areas after heavy rains would further minimize disturbance. Of course moves on terrain in a sensitive state would probably be unavoidable so some unacceptable disturbance would be inevitable. However it is a conclusion of this study that one trip may be made over any terrain type at any time without a risk that the resulting disturbance will be augmented by erosion.

Where repeated use of a trail on peat is unavoidable, keeping routes clear of water courses or areas topographically favourable for the collection of runoff will prevent later degradation of the ruts. The objective of route planning in this case is preservation of the peat slurry. Its insulating properties are not markedly less than undisturbed peat and its presence may prevent thermal erosion.

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